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Effectiveness of Mechanical Test in Ascertaining Moisture Damage of Asphalt Mixtures.

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EFFECTIVENESS OF MECHANICAL TEST IN ASCERTAINING MOISTURE DAMAGE OF ASPHALT MIXTURES

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ABSTRACT

Infiltrated moisture combined with repeated action of traffic and environmental loading generates distresses which adversely affect the durability of asphalt pavements. Almost 94% of states' highway agencies use either the Loaded Wheel Tracking (LWT) test or the Modified Lottman test to capture asphalt mixtures' moisture susceptibility. However, the current LWT and the modified Lottman test practice lack accuracy in relating laboratory performance to observed field performance.

The study's primary objective was to evaluate the capability of different laboratory mechanical test methods to predict moisture susceptibility of asphalt mixtures. Asphalt binder and mixture experiments were conducted to achieve the objective of the study. The study utilized two asphalt binder types (PG 67-22 and PG 70-22) along with three aggregates (limestone, crushed gravel, and semi-crushed gravel). Both the asphalt binder and asphalt mixture experiments included five levels of moisture conditioning; 1) short-term aging (control); 2) single freeze-thaw (FT-1); 3) triple freeze-thaw (FT-3); 4) MiST 3500; and 5) MiST 7000. The asphalt binder experiment included rheological characterization of conditioned asphalt binder using Frequency Sweep test and MSCR test. Seven 12.5mm NMAS asphalt mixtures were employed in the asphalt mixture experiment. A suite of mechanical test methods, including the LWT, the modified Lottman, and the SCB test, was conducted on moisture conditioned asphalt mixtures.

Freeze-thaw and MiST conditioning resulted in a stiffer asphalt binder when compared to the control. The LWT and the SCB test exhibited an increase in moisture damage associated with progressive freeze-thaw and MiST conditioning of asphalt mixtures. In contrast, the modified Lottman test showed consistent test results only with freeze-thaw conditioning. Observing moisture damage caused by conditioning levels made it possible to predict moisture susceptibility of the asphalt mixture. Employed mechanical test methods reported an increase in moisture resistance of asphalt mixtures with either SBS modified asphalt binder or with anti-strip asphalt binder when compared to conventional asphalt binder. Furthermore, the SCB test and the LWT test results showed a similar trend in predicting the aggregate type's effect on the asphalt mixture's moisture susceptibility. The SCB test exhibited the potential to capture moisture damage in asphalt mixtures. To standardize the SCB test as a moisture damage test, a thorough investigation to relate laboratory performance to observed field performance should be done.

CHAPTER 1. INTRODUCTION AND RESEARCH APPROACH

1.1. Background

Asphalt pavements are subjected to various environment and traffic loadings during their service life which adversely affect the durability and life cycle cost of the pavements [1]. The presence of moisture in asphalt pavement is inevitable; it can infiltrate via cracks, interconnected air voids, pavement shoulders, and rising groundwater levels [2]. Infiltrated moisture can induce damage in asphalt pavements by generating cyclic hydraulic pressure inside the void structure under repeated traffic loading or by the action of freeze-thaw [3]. Moisture damage is characterized either by adhesive failure, cohesive failure, or a combination of both failure modes [4]. Adhesive failure represents a loss of adhesion between the asphalt binder film and the aggregate surface (stripping). Cohesive failure is characterized by a reduction of asphalt mixture stiffness due to loss of cohesion in the asphalt binder matrix [4].

Since the onset of asphalt paving technology, moisture-induced distresses like stripping, raveling, cracking, and rutting have been observed in asphalt pavements [5]. Over the years, various laboratory test methods, both qualitative and quantitative, have been developed to evaluate moisture damage in asphalt mixtures. The qualitative test methods evaluate the moisture susceptibility of asphalt mixtures by measuring the semi-subjective and subjective performance indicator of moisture damage, and include test methods like the boiling water test (ASTM D 3625,[6]), the static immersion test (AASHTO T 182,[7]), etc. On the other hand, the quantitative methods develop criteria to evaluate or predict moisture damage in asphalt mixtures based on inferenced drawn from the laboratory testing. Some of the test methods used for quantitative analysis are the immersion-compression test (AASHOT T 165,[8]), the modified Lottman test

(AASHTO T 283,[9]), and the Hamburg-loaded wheel tracking test (AASHTO T 324,[10]) [5]. The laboratory-performed quantitative tests methods have been considered better than qualitative test methods to assess or predict moisture susceptibility of asphalt pavements test methods [5].

1.2. Problem Statement

According to a recent survey, 94% of the state highway agencies of the USA require at least one test method to evaluate the moisture sensitivity of asphalt mixtures in mix design specification [11]. The two most preferred moisture damage tests by state highway agencies (approximately 85% of agencies) are the modified Lottman test and the LWT test [11]. The most widely used of the two is the modified Lottman test which uses the Tensile Strength Ratio (TSR) of conditioned to unconditioned asphalt mixture specimens to evaluate moisture damage [11]. Further, researchers assessed the moisture susceptibility of five different asphalt mixtures obtained from different states using the modified Lottman test. They reported inconsistent correlation between the TSR value obtained from the laboratory testing and the known field performance of the asphalt mixtures as provided by the state's highway agencies [13]. Studies have also reported that the modified Lottman test lacks repeatability due to its sensitivity to air voids distribution and saturation levels [12-14].

The second most widely used test for evaluating moisture sensitivity of asphalt mixtures among the state highway agencies is the LWT test [11]. In recent years, the LWT test has gained popularity among the state agencies and asphalt contractors over the modified Lottman test due to its repeatability and simple testing procedure [12]. As the name suggests, the Hamburg-wheel tracking device (also known as the Loaded Wheel Tracker) was developed in Hamburg, Germany by Helmut-Wind, Inc. and was introduced in the USA in 1990 [15]. The LWT test uses a loaded-rolling steel wheel (cyclic load) across the surface of submerged asphalt mixtures and has been found to better simulate field conditions than the modified Lottman test [15]. Numerous studies have evaluated the effectiveness of the LWT test to ascertain moisture sensitivity of asphalt mixtures and found a good correlation among laboratory results and observed field performance [13-17]. However, there are some studies that have reported the inadequacy of the LWT test in predicting field performance of moisture susceptible asphalt pavements [18-21].

The LWT test uses a pass/fail criterion to evaluate moisture susceptibility, this does not provide consistent reporting of the performance-related parameter. Moreover, each state highway agency chooses a different pass-fail criterion which further highlights the inconsistency of this test method to capture moisture susceptible asphalt mixtures [19]. Because of this, researchers have reported a need to establish a standard test procedure for the LWT test to verify the field performance of moisture susceptible asphalt mixture with different mixture characteristics [20].

Over the years, researchers have incorporated laboratory moisture conditioning protocols to simulate the effects of field conditions, which includes freeze-thaw conditioning procedure as per AASHTO T 283 [9] and Moisture-induced stress tester (MiST) as per ASTM D 7870 [21]. Inclusion of these conditioning protocols prior to laboratory test have resulted in better prediction of moisture susceptible asphalt mixtures [14]. Despite numerous research efforts, moisture-induced distresses continue to be a challenge for the United States and various parts of the world [12]. Researchers have demonstrated that current test protocols for evaluating moisture sensitivity offer some limitations in distinguishing between moisture-sensitive asphalt mixtures and moisture resistant ones. Therefore, there is a need for a simple performance test that can provide a consistent mechanistic evaluation of moisture damage in asphalt mixtures.

1.3. Research Objectives

The study's primary objective was to evaluate the capability of different laboratory mechanical test methods to characterize moisture damage in asphalt mixtures. Specific objectives included:

a. evaluate the effect of different moisture conditioning levels on asphalt binder rheology,
b. evaluate the effect of asphalt binder type on moisture susceptibility of asphalt mixtures,
c. evaluate the effect of aggregate type on moisture susceptibility of asphalt mixtures, and
d. evaluate the effect of different moisture conditioning levels on the moisture susceptibility of asphalt mixtures.

1.4. Research Scope

The objectives of the study were achieved by performing asphalt binder and asphalt mixture experiments. The asphalt binder experiment included an unmodified PG 67-22 and a styrene-butadiene-styrene (SBS) modified PG 70-22 asphalt binder, along with five levels of moisture conditioning: short-term aging following the rolling-thin film oven (RTFO) Test (per AASHTO T 240,[22]); single- freeze-thaw (FT-1); triple- freeze-thaw (FT-3); MiST 3500; and MiST 7000. Further, the effect of moisture conditioning on rheological properties of asphalt binders was evaluated using the Dynamic Shear Rheometer (DSR).

A total of seven 12.5mm Level 2 asphalt mixtures were evaluated in the asphalt mixture experiment. Two asphalt binder types (PG 67-22 and PG 70-22) and three aggregate types (limestone, Crushed Gravel, and Semi-Crushed Gravel) were utilized in the asphalt mixture experiment. Consistent with the asphalt binder experiment, five conditioning levels were utilized in the asphalt mixture experiment. The five conditioning levels included short-term aging (STA, AASHTO R 30 [23]) of the loose mixture (Control); single freeze-thaw-; triple freeze-thaw; MiST 3500 cycles; and MiST 7000 conditioning cycles of compacted mixtures. A suite of laboratory mechanical tests, modified Lottman; Loaded Wheel Tracking (LWT); and the Semi-Circular Bend (SCB) tests were performed to evaluate the asphalt mixtures.

1.5. Research Approach

Figure 1.1 presents a detailed outline of the research approach adopted for this study.

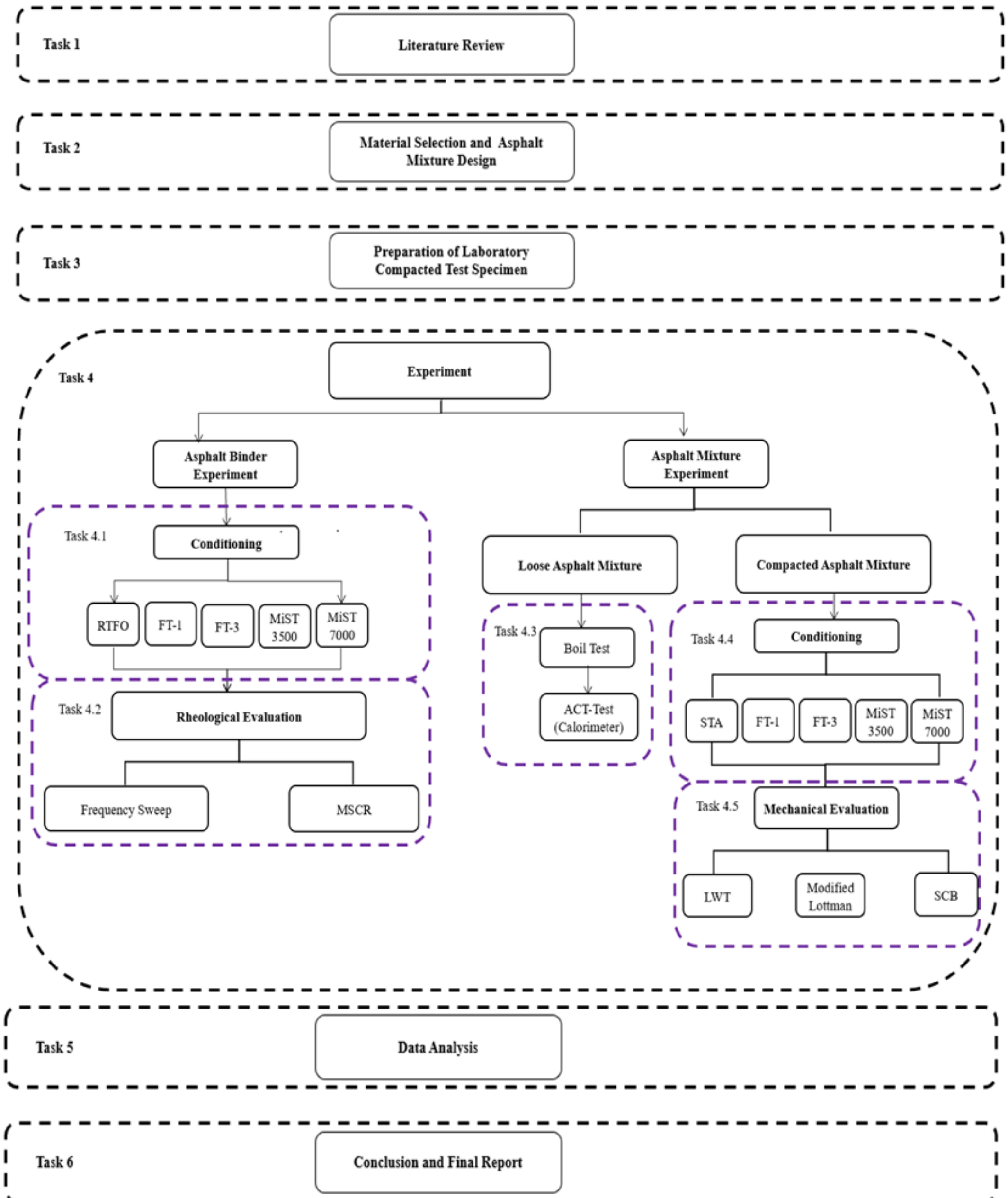

Figure 1.1. Research Approach

Task 1: Literature Review.

The objective of this task was to collect and review published literature from a variety of sources regarding completed and ongoing research studies on moisture-induced damage. The task included literature from a variety of sources to understand the process of moisture intrusion and its effect on the properties of asphalt pavement and its constituent materials. State-of-the-art literature helped in understanding the development of moisture damage theories and laboratory test methods. The review included contemporary advancement in testing methodologies, analysis approach, and the response of moisture-induced distresses. Candidate laboratory test methods and available moisture conditioning procedures were investigated thoroughly. The task consisted of the review of literature from sources such as standard test methods (AASHTO and ASTM), Transportation Research Information Database (TRID), National Technical Information Services (NTIS), and Computerized Engineering Index (COMPENDEX).

Task 2: Material Selection and Asphalt Mixture Design

The objective of this task included the selection and characterization of asphalt mixture component materials (asphalt binders and aggregates) for the design of asphalt mixtures. Two asphalt binder types (PG 67-22 and PG 70-22) were selected and characterized as per AASHTO R 29 [24], "Standard Practice for Grading or Verifying the Performance Grade (PG) of an Asphalt Binder," and the Louisiana standard of Specifications for Roads and Bridges (LADOTD, 2016 [25]). Three aggregate types were considered: a) low moisture susceptible limestone aggregate with high angularity, (absorption < 2%); b) high moisture crushed Gravel (absorption > 2%) susceptible with high angularity; and c) high moisture susceptibility smooth and round gravel (absorption > 2%) with low angularity. Furthermore, the physical properties of the selected aggregate were evaluated to meet LADOTD 2016 specifications for aggregates for asphalt mixtures.

A total of seven 12.5mm NMAS levels-2 asphalt mixtures were utilized in this study. Table 1.1 presents the asphalt mixtures that were designed for optimum asphalt binder content during this task in accordance with AASHTO R 35 [26], Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA), AASHTO M 323 [27]. Standard Specification for Superpave Volumetric Mix Design and Section 502 of the 2016 Louisiana Standard Specifications for Roads and Bridges [25]. Mixtures M1, M2, and M3 comprise PG 67-22 asphalt binder, while mixtures M4, M5, and M6 comprise PG 70-22 asphalt binder.

Mixture M1 incorporated limestone aggregate which has low absorption content with high coarse aggregate angularity and is referred to as a moisture-resistant asphalt mixture. Further, M2 and M3 represented more moisture-sensitive asphalt mixtures than M1 due to the inclusion of Gravel, which has high absorption content. Additionally, M1, M2, and M3 were laboratory prepared and compacted using a PG 67-22 asphalt binder, whereas mixtures M4, M5, and M6 were also laboratory prepared but used PG 70-22 asphalt binder. M4, M5, and M6 follow the same aggregate type as was used for M1, M3, and M3, respectively. Mixture M7 was obtained from an asphalt plant as a loose mixture which consisted of limestone aggregates with PG 67-22 asphalt binder like mixture M1, but includes an anti-stripping agent to represent advanced technology moisture-resistant asphalt mixture

Table 1.1. Asphalt Mixture Composition

Mixture Id:	NMAS (mm)	Binder Id:	Aggregate Type	ASA	RAP Content (%)	Moisture Sensitivity
M1	12.5	PG 67-22[1]	Limestone	N/A	N/A	Low[a]
M2			Crushed Gravel	N/A	N/A	High[b]
M3			Semi-Crushed Gravel	N/A	N/A	High[b]
M4	12.5	PG 70-22[1]	Limestone	N/A	N/A	Low[a]
M5			Crushed Gravel	N/A	N/A	High[b]
M6			Semi-Crushed Gravel	N/A	N/A	High[b]
M7	12.5	PG 67-22[1]	Limestone	0.6% (LA-2)	19%	Low[a]

Note: [1] Meeting 2016 Louisiana DOTD specifications for Road and Bridges; RAP: Recycled asphalt pavement content; n/a: not applicable; LA-2: Liquid anti-strip additive; Low: low moisture susceptible aggregate (water absorption < 2%); High: high moisture susceptible aggregate (water absorption > 2%)

Task 3: Prepare Laboratory Compacted Test Specimens:

The objective of this task was to prepare laboratory test specimens considered in this research according to their standard test protocols. Sufficient asphalt mixture component materials (asphalt binder and aggregates) were secured. Laboratory mixture specimens were prepared according to the specific requirements of each proposed test. Specifically, a Superpave gyratory compactor (SGC) was used to compact all cylindrical specimens. Table 1.2 provides the asphalt mixture test details: test protocol; engineering properties evaluated; specimen geometry; and testing conditions (temperature, conditioning type). The target air voids for all specimens were restrained to 7.0 ± 0.5%. A minimum of three samples were compacted for each test evaluated.

Table 1.2. Asphalt Mixture Test Conditions

Test	Test Protocols	Engineering Properties	Specimen Geometry	Test Temperature, Conditioning Type
Semi-circular Bend (SCB)	ASTM D8014	Intermediate Temperature: Fatigue Cracking Resistance	150 mm diameter x 57 mm	25°C
Loaded Wheel Tracking (LWT)	AASHTO T 324	Rutting Susceptibility and Moisture Resistance	150 mm diameter x 60 mm	50°C, wet condition
Modified Lottman Test (ITS)	AASHTO T 283	Moisture Resistance	150mm diameter x 95mm	25°C, wet and dry condition

Task 4: Laboratory Experiments

The objective of this task was to perform a comprehensive evaluation of the asphalt binders and asphalt mixtures using selected rheological and mechanical tests, respectively. The objective is sub-divided into subtask for consistent laboratory testing of the study, as shown in Figure 1.1. The asphalt binder experiment included moisture conditioning of the asphalt binders to five levels: a) Short term or Rolling thin film oven aging (RTFO); b) FT-1; c) FT-3; d) MiST 3500; and c) MiST 7000. Moisture conditioned asphalt binders were rheological characterized using a Frequency Sweep and Multiple Stress Creep Recovery Test. Furthermore, the asphalt mixture experiment included similar levels of moisture conditioning as was done in the asphalt binder experiment: a) Short-term aging (control); b) FT-1; c) FT-3; d) MiST 3500; and c) MiST 7000. A suite of mechanical testing was employed for asphalt mixtures to evaluate the effect of moisture conditioning.

Subtask 4.1- Moisture Conditioning of Asphalt Binders

Five conditioning levels were considered in the asphalt binder experiment. The first conditioning level (i.e., control) consisted of short-term aging of asphalt binder following the RTFO protocol [22]. For the remaining four levels of conditioning, RTFO aged asphalt binder was poured into a

PAV pan to achieve a uniform thickness of 3.2mm. Then, the specimens in the PAV pans were subjected to single freeze-thaw- (FT-1), triple- freeze-thaw- (FT-3), MiST 3500- and MiST 7000 conditioning cycles for the second, third, fourth, and fifth conditioning levels, respectively. A detailed description of the Freeze-Thaw and MiST conditioning levels is provided in the asphalt mixture experiment section.

Subtask 4.2 Rheological Evaluation

Rheological evaluation of the above-mentioned conditioned asphalt binders was performed using the DSR.

Frequency Sweep at multiple Temperatures: The frequency sweep test was performed according to AASHTO T 315 [28], "Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)". The test was performed at frequencies ranging from 0.1 to 100 rad/s and at temperatures of 5°, 20°, and 45°C. The test data obtained was used to construct master curves for dynamic shear modulus (G*) and phase angle (δ), from which the effect of moisture conditioning on asphalt binder rheological properties was determined.

Multiple Stress Creep Recovery (MSCR): The effect of moisture damage on the rutting performance of asphalt binders was characterized using the MSCR test at 67°C, in accordance with ASTM D 7405 [29]. The test applies a creep load for 1-second and allows recovery for 9-seconds using a 25-mm diameter specimen size with 1-mm gap geometry. The test method consists of two stress levels, 0.1kPa and 3.2kPa, and each stress levels consist of 10 creep-recovery cycles. The non-recoverable creep compliance (*Jnr*) and percent elastic recovery (R) were determined.

Subtask 4.3: Asphalt Mixture Evaluation

The effect of moisture on short-term aged loose asphalt mixtures was evaluated using the boil test. Asphalt Compatibility Tester (ACT) was utilized to quantify the stripping observed by boil test.

Boil Test: The boil test was conducted according to ASTM D 3625 "Standard Practice for Effect of Water on Asphalt-Coated Aggregate Using Boiling Water" [30], the test was performed to evaluate the resistance of asphalt film coating on the surface of aggregate particles to moisture damage after a short duration of boiling underwater. 250g of the asphalt mixture was added to boiling water for about 30 minutes. After 30 minutes of boiling, the sample was measured for the percentage of aggregate surface that retained the asphalt binder coating according to visual observation. The percentage of aggregates that lost their asphalt binder coating was recorded as a measure of the loss of adhesion in the loose asphalt mixture due to moisture.

Asphalt Mixture Calorimeter Measurement using the Asphalt Compatibility Tester (ACT): The ACT was run to measure the color change that occurs after subjecting loose asphalt mixture samples to the boil test [31]. The test was performed to evaluate the resistance of asphalt film coating on the surface of aggregate particles to moisture damage after a short duration of boiling underwater. 250g of the mixture was added to boiling water for about 30 minutes. After 30 minutes of boiling, the sample is measured for the percentage of aggregate surface that did not retain its asphalt binder coating (percent loss) using the Asphalt Compatibility Tester (ACT). The ACT quantifies the change in the color of the asphalt mixture due to boiling by measuring the percent loss of asphalt binder before and after boiling [32,33]. The percent loss was measured as the effect of the moisture conditioning (boiling in water) on the adhesive strength between the asphalt binder and the aggregates in the mixture [67].

Subtask 4.4: Asphalt Mixture Conditioning

Five conditioning levels were considered in the asphalt mixture experiment. The first conditioning level (i.e., control) consisted of short-term aging of loose asphalt mixture samples following AASHTO R 30 [49], "Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)" prior to compaction in the gyratory compactor. The other four conditioning levels were performed on compacted asphalt mixtures samples by using freeze-thaw conditioning and MiST conditioning as follows:

Freeze-Thaw Conditioning: For the second and the third level of conditioning, the study employed freeze-thaw conditioning of the asphalt mixtures following AASHTO T 283 "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage" [9]. The freeze-thaw (single and triple) conditioning involved saturation of an asphalt mixture specimen to a degree of 70-80% by applying a vacuum of 10-26 in. Hg. The saturated vacuum specimens were immediately wrapped in a plastic film and sealed in a plastic bag with 10ml water. The second level (FT-1, single- freeze-thaw) involved placing of the saturated sealed specimen in a -18C freezer for 16 hours. After completion of 16hrs, the plastic bag and film were removed, and the specimen was kept in a 60°C water bath for 24hrs. Further, the third level (FT-3, triple-freeze-thaw) included three repetitions of the FT-1 conditioning of the saturated specimen. It is worth noting that for the three conditioning cycles, specimens were removed from the 60°C water bath, tightly covered with plastic wrap, and then placed back in the freezer to repeat freeze-thaw cycles two more times. After conditioning, the specimens were removed from a 60ºC water bath and placed in another water bath at 25ºC before testing. After specimens achieved the desired level of conditioning, they were placed in a 25°C water bath for 2 hours and tested immediately afterwards.

MiST Conditioning: The compacted asphalt mixture specimens were subjected to MiST conditioning as per ASTM D 7870 "Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure [21]." Compacted asphalt mixture specimens were subjected to an adhesion time of 20hrs at 60°C in a water-filled MiST chamber. After completion of the adhesion cycle, pore pressure cycles of 40psi were introduced in the chamber. The MiST conditioning included two levels; MiST 3500 (level four), which included 3500 pressure cycles, and MiST 7000 (level five), which used 7000 pressure cycles. After attaining the conditioning level, the specimens were placed in a 25°C water bath for 2 hours and tested immediately afterwards.

Subtask 4.5: Mechanical Evaluation

A suite of mechanical testing was employed to evaluate the effect of asphalt binder type, aggregate type, and moisture conditioning protocol on asphalt mixtures, as well as to compare the effectiveness of the test methods in ascertaining moisture sensitivity of asphalt mixtures.

Loaded Wheel Tracking (LWT) Test: The loaded-wheel test was conducted in accordance with AASHTO T 324 "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA) [10]." Four cylindrical asphalt mixture specimens of 150 mm diameter and 60 mm thickness were compacted using SGC with an air void content of 7 ± 0.5%. The LWT test creates damage by applying a loaded rolling-steel wheel (158lb) across the surface of the submerged specimens at 50°C and is considered as a torture test. The test was run in two pairs of replicates at 52passes/min for 20,000 passes or a 25mm rut depth, whichever was achieved first. The total rut depth accumulated after completion of the test was reported as a measure of moisture damage. In addition, stripping inflection point (SIP) was computed and reported as a measure of moisture damage for the mixtures evaluated. Asphalt mixtures subjected to different levels of moisture conditioning (e.g., dry, MiST, and freeze-thaw cycles) were evaluated using the LWT.

Modified Lottman Test: The modified Lottman test was conducted in accordance with AASHTO T 283 "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage [9]". The test procedure uses two sets of specimens compacted to 150-mm in diameter and 95-mm in thickness at 7.0±0.5% air void: 1) the control set without conditioning and 2) the conditioned set with partial vacuum saturation and an optional freeze-thaw cycle. A split tensile or indirect tensile test at 25°C is performed on each sample, and a ratio (Tensile Strength Ratio, i.e. TSR) of the indirect tensile strength of the conditioned samples to the control group is determined as an indicator of induced-moisture damage. A minimum TSR of 0.70 to 0.80 is often used as a standard criterion.

Semi-Circular Bending (SCB) Test: The SCB test was performed in accordance with the ASTM D 8044 [34] "Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures." The test characterizes the fracture resistance of asphalt mixtures based on fracture mechanics principals, the critical strain energy release rate, which is also referred to as the critical value of J-integral or J_c. The test uses a three-point bending configuration over semi-circular specimens of 150mm diameter by 57mm thick with at least two different notch depths. The semi-circular specimens were loaded monotonically until fracture failure under a constant crosshead deformation rate of 0.5 mm/min at 25°C. The load and deformation data were continuously recorded and processed to determine the critical value of J-integral (J_c). The higher the Jc value of a mixture, the higher its fracture resistance at intermediate temperatures, and vice versa. Asphalt mixtures subjected to different levels of moisture conditioning were evaluated using the SCB.

Task 5: Data Analysis:

The objective of this task was to evaluate the reliability of a candidate test procedures through a series of comparative analyses between various types of asphalt mixtures among selected moisture conditioning protocols. The reliability is a measure of how well a test method differentiates between different samples. Thus a difference in test results between low and high moisture susceptible asphalt mixtures by a candidate test method was a measure of the reliability. The repeatability is a measure of random errors in individual measurements under the same condition. A lower value of the coefficient of variation (CoV) in measurements is desirable for a good test method. Additional statistical analyses, such as two-sample t-tests, analysis of variance (ANOVA), and correlation analysis were performed to determine the statistical significance of the effect of the different asphalt binder and asphalt mixture conditioning schemes on asphalt binder and asphalt mixture performance parameters (i.e., SCB- Jc, LWT rut depth, etc.)

Task 6: Conclusion and Final Report:

In this task, a final report was prepared to summarize and document all findings, experiments, results, conclusions, and problems encountered during the project period. After a thorough evaluation of moisture conditioning procedures and mechanical test methods, the appropriate conditioning and test combination were determined and recommend for an implementation consideration into the Louisiana Standard Specifications for Roads and Bridges. Recommendations for future research needs were also addressed.

CHAPTER 2. LITERATURE REVIEW

In early 1960s, the American Association of State Highway Officials (AASHO) developed the first generation of pavement design guide considering only traffic loading to determine pavement layer thickness [38]. The guide used equations which correlated asphalt pavements' thickness to cumulative traffic loads and did not take environmental loading (moisture, temperature, and freeze-thaw cycles) into consideration, only a regional factor related to climate was used [38]. Although traffic loading significantly contributes to deterioration and failure of asphalt pavements, the environmental loading often accelerates traffic loading deterioration. In most cases the combined loading effect in asphalt pavements can lead to early maintenance and rehabilitation needs [39]. In late 1970's, asphalt pavements in the United States started to experience a significant number of moisture-related distresses associated with moisture susceptibility of asphalt mixtures, and moisture damage is considered as a nationwide problem to this day [38].

With the advancements in technology and considerable resources from Federal and State agencies, the knowledge of researchers on the impact of environmental loading, tools for simulating temperature and moisture conditions, and methods to mitigate those impacts have improved significantly [38]. Despite numerous research efforts, moisture damage in asphalt pavements has been considered as a major reason for increased maintenance and rehabilitation budgets need by federal and state highway agencies [40].

2.1. Moisture Susceptibility

Failure in asphalt pavements are categorized by two modes: stability and durability. The stability-related mode refers to design and displacement problems of asphalt mixture under normal loading, while a durability-related failure mode is identified by pavement age and environmental conditions [40-41]. Moisture damage in asphalt pavements is characterized as a durability related failure mode and occurs in two forms, softening and stripping [42]. Stripping is characterized by a loss of adhesion, i.e. the breaking of bonds between the asphalt binder and aggregate surface due to intrusion of moisture. Softening is identified as a loss of cohesion among the asphalt binder film or asphalt binder matrix, which is further responsible for a reduction in strength and stiffness of the asphalt mixture [42]. A combined effect of repeated traffic loading and freeze-thaw action under saturated pavement conditions generates cyclic hydraulic pressure in asphalt pavements and can lead to premature failure in asphalt pavements, refer to Figure 2.1 [2]. The induced moisture damage accumulates and can cause distresses like stripping, premature rutting, raveling, and cracking observed in asphalt pavements, refer to Figure 2.2 [2].

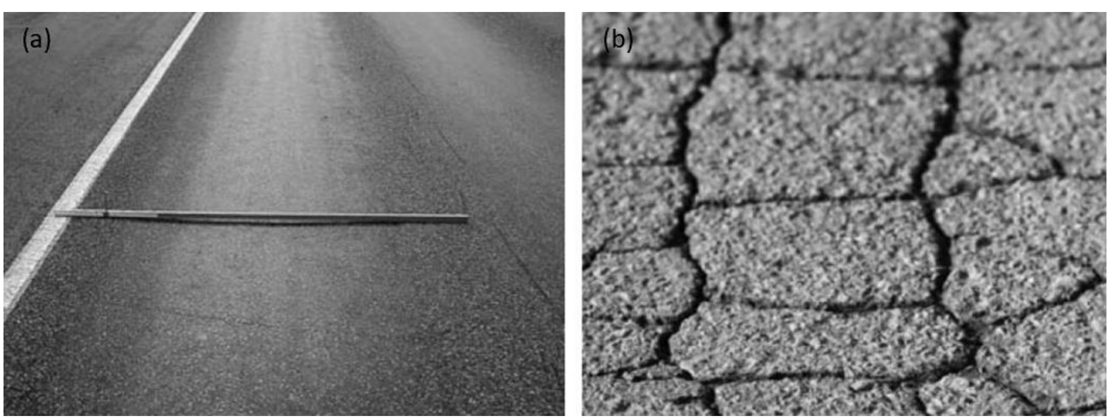

Figure 2.1. Premature failure in asphalt pavements: a) rutting and b) fatigue cracking [2]

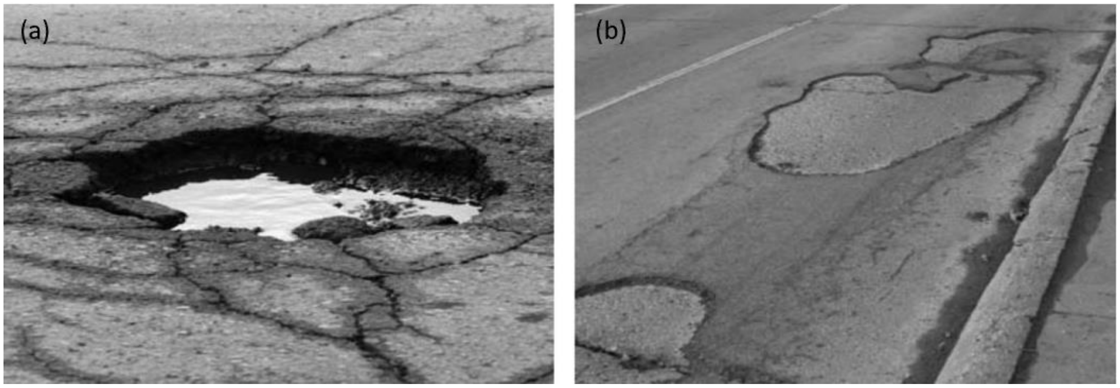

Figure 2.2. Moisture induced distresses: a) potholes and b) declamation [2].

The two failure mechanisms (i.e., adhesive and cohesive failure) may induce distresses such as stripping, raveling, cracking, and rutting, and can lead to premature failure of asphalt pavement [1]. The adhesion and cohesion mechanism of an asphalt mixture has been classified into three categories: a) mechanical, b) chemical, and c) thermodynamic [42]. The mechanical bond between the asphalt binder and aggregate surface is characterized by the mechanical interlocking of the asphalt binder into the aggregate pores and is linked to the surface characteristics of the aggregates and the tensile strength of asphalt binder. A chemical bond links the asphalt binder and the aggregates, the bond depends upon the surface charge and pH of the asphalt mixture components. The ability of the asphalt binders to coat the aggregate surface is dependent upon the viscosity and surface tension of the asphalt binder and is referred to as the "wetting property" of the asphalt binder. An asphalt binder with low surface tension and viscosity will be able to spread over and better coat the aggregate surface [42]. Researchers have highlighted the dependency of environmental conditioning on the adhesion and cohesion failure mechanisms, which further accentuates the difference in stripping mechanism for a hot-dry area to hot-wet, cold-dry, and cold-wet environment [43-45]. Moisture damage in asphalt pavements can arise from constructional flaws such as inadequate pavement draining, inadequate compaction, excessive dust coating on aggregate, inadequate drying of aggregate, weak and friable aggregate, etc. [42].

Furthermore, the presence of moisture can cause failure of adhesion and cohesion mechanics by the following phenomena:

Detachment: The physical separation of the asphalt binder from the aggregate due to either the presence of interstitial pore moisture or the permeation of moisture through the asphalt binder film reaching the interface between asphalt binder and aggregates [42]. The presence of bond energy between asphalt binder and the aggregates, i.e. surface free energy, resist the peeling of the asphalt binder film. The presence of moisture decreases the surface energy between the asphalt binder and aggregate due to stronger polar orientation forces between moisture and aggregate than asphalt binder and aggregate [42].

Displacement: The mechanical effect of free flow of moisture in asphalt pavements leads to displacement of the asphalt binder from the aggregate surface. The moisture permeates to the aggregate surface by breaking the asphalt binder coating from the aggregate surface [45].

Spontaneous Emulsifications: Occur when the moisture reacts with asphalt binder and causes a loss of tenacity of the asphalt binder. The presence of traffic loadings under saturated conditions is mainly responsible for this process [42].

Film rupture: Film rupture is characterized by fissures which occurs under traffic loading at the aggregate edges and corners. Once a break in film is established, the moisture infiltrates and causes stripping [44].

Pore Pressure: Traffic loading causes a reduction in void space and entraps the water inside the voids. The continued action of traffic might generate extensive pore pressure inside the voids causing stripping of asphalt binder from the aggregate surface [45].

Hydraulic Scouring: Traffic loading under saturated asphalt pavements causes moisture ingression in front of tires and removal at the back of the tires. The pressure flow tends to strip the asphalt binder from the aggregates. The scouring action is exacerbated by the presence of dust or abrasive aggregates on the surface of the roadway [45].

2.2. Factors Affecting Moisture Susceptibility

A survey conducted in 2002 as a part of Federal Highway Administration project “Rehabilitation techniques for stripped asphalt pavements” reported that the extent and severity of moisture damage in asphalt mixtures is related to the environment, aggregate characteristics, asphalt binder, and mixture properties [42]. The study reported various factors responsible for moisture damage, specifically environment, asphalt binder, aggregate shape characteristics, and mixture density.

Environment

The Federal Highway Administration (FHWA) divides the United States into four climate regions (Figure 2.3); Dry Freeze, Wet Freeze, Dry-Non freeze, and Wet-Non-freeze.

Climate Zone	Annual Rainfall (Inch)	Freezing Index (°F-Days)
Wet Non-Freeze	> 28	< 100
Wet Freeze	> 28	> 100
Dry Non-Freeze	< 28	< 100
Dry Freeze	< 28	> 100

Note: 1 inch = 2.54 cm;
Temperature (unit in °F) = Temperature (unit in °C) × 1.8 + 32.

Figure 2.3. Four Climate Regions based on FHWA [46].

Regions with high annual rainfall are expected to exhibit higher moisture damage and stripping [42]. Thermal Cracking in asphalt pavements is primarily related to environmental loading and is prominent with small seasonal (Dry Non-freeze) temperature differential areas and large diurnal (Dry Freeze) temperature differential areas [42]. Whereas, for wet freeze or wet non-freeze areas fatigue cracking is prominent. The change in asphalt binder stiffness due to the combined effects of environment and traffic loading hampers the ability of the asphalt pavements to resist fatigue cracking. Moreover, areas with high average annual rainfall experience increased saturation of pavement layers, which further weakens the support and accelerates fatigue cracking [47].

Asphalt Binder

The physical and chemical characteristic of the asphalt binder are important to understanding the behavior of asphalt mixtures in the presence of moisture. Researchers have investigated the effect of asphalt binder film thickness and have established a relationship between the asphalt binder film thickness and type of failure (cohesive or adhesive) [50-52]. Asphalt mixtures with thinner asphalt binder film exhibit higher cohesive tensile strength than adhesive tensile strength [51]. Researchers have investigated the performance of modified asphalt binders and reported an increase in asphalt mixture performance. Asphalt binders modified with elastomers showed an increase in fatigue and rutting performance, whereas plastomer-modified asphalt showed an increase in rutting performance only. Elastomer-modified asphalt exhibited increase in moisture resistant of asphalt mixtures [53-54].

Aggregate Shape Characteristics

Aggregate shape impacts the mechanical adhesion between the asphalt binder and aggregate. The important characteristics of aggregates which contribute to the mechanical interlock of asphalt binders and aggregates are physical interlocking, surface area, and porosity [56-57]. Researchers have reported that aggregate texture and angularity play an important role in asphalt mixture's resistance to deformation and sliding of the aggregate on the asphalt binder film [56]. The surface texture of aggregate is a manifest of the pores structure of the aggregate and can be characterized either as smooth or rough. Angularity is measure of shape of the aggregate, round or angular. An increase in surface area due to increase in angularity will result in higher total bond energy [55].

However, an increase in aggregate angularity can also cause puncturing of the asphalt binder film, which can further allow the intrusion of moisture to aggregate surfaces. Figure 2.4 presents the difference between angularity, texture, and form.

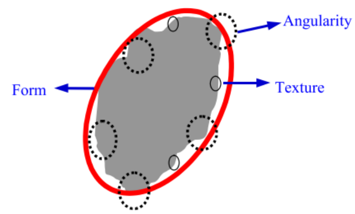

Figure 2.4. Schematic of aggregate shape: Angularity, Foam and Texture [30].

Masad et al. evaluated the effect of aggregate properties on asphalt mixtures' performance. In the study, researchers characterized asphalt mixtures with three different aggregates: limestone, granite, and gravel. The granite aggregate blend manifested the highest texture and angularity. followed by limestone, and then gravel. The asphalt mixtures were tested in both dry and wet conditions using LWT and Dynamic Modulus Test (DM). The researchers reported asphalt mixtures consisting of granite and limestone outperformed gravel asphalt mixtures in both dry and wet conditions due to high angularity [49].

Mixture Density

Moisture damage in asphalt pavements depends upon the extent and ease with which moisture can infiltrate and is directly linked to the air void and permeability of the asphalt mixture. Densely graded asphalt mixtures will exhibit less moisture susceptibility than poorly graded or gap graded asphalt mixtures [47]. Next, the relationship between asphalt mixtures moisture susceptibility, void structure, and pore pressure was evaluated. The study used different gradations to represent the distributions of air voids. The asphalt mixtures were compacted to a target of 7% air void and were tested using the modified Lottman test [50]. Researchers investigated an average diameter size of the aggregate where moisture damage is at maximum and referred to it as “pessimum size”. At a “pessimum” air void, the moisture infiltrates with ease but drains out with difficulty, leading to extensive moisture damage [50].

2.3. Moisture Susceptibility Tests

Over the years, numerous test methods have been developed to identify moisture susceptibility of asphalt mixtures. These test methods can be grouped into two categories: tests on loose asphalt mixtures and tests on compacted asphalt mixtures.

Test on Loose Asphalt Mixtures.

Static Immersion Test: AASHTO standardize this test method as T 182 [7] “Standard Method of Test for Coating and Stripping of Bitumen Aggregate Mixtures”. The test method involves curing of the loose asphalt mixtures for 2 hours at 60°C, followed by keeping the mixtures in a jar with distilled water at 25°C for 16 hours. AASHTO has established a visual inspection criterion to estimate the stripping of asphalt binder from the aggregate surface; the retention of the asphalt binder on the aggregate surface must be more than 95% for moisture resistant asphalt mixtures. The curing method utilized has some limitations; studies have reported the use of longer curing time for better prediction of moisture sensitive asphalt mixtures [53]. The test uses a subjective approach and fails to evaluate a fundamental engineering property to establish a good correlation among the laboratory-observed and field performance of asphalt mixtures [53].

*Texas Boiling Test**:*** Developed by Kennedy et al. [57], the test method involves boiling of loose asphalt mixtures for ten minutes. The boiled mixture is dried using a paper towel and inspected visually based on the criteria standardized by ASTM as D 3625 “Standard Practice for Effect of Water on Asphalt-Coated Aggregate using Boiling visual assessment”. Although the test method is quick in evaluating moisture sensitivity of asphalt mixtures, the method lacks in mechanistic evaluation and inclusion of traffic loading [57].

Bitumen Bond Strength Test: AASHTO standardize this test as T 361 [58] “Standard Method of Test for Determining Asphalt Binder Bond Strength by Means of Binder Bond Strength (BBS) Test”. The test is used to evaluate the adhesion between the asphalt binder and the aggregate by quantifying the tensile force required to pull off a stub attached with asphalt binder to the aggregate surface. The test is conducted under controlled temperature and moisture conditions. The pull of tensile strength and dominant failure mode (adhesive or cohesive) are used to characterize the bonding potential and affinity of the asphalt binder to the aggregate surface.

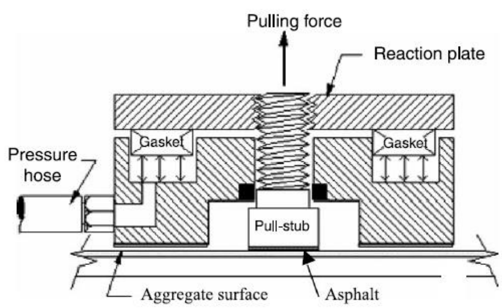

Figure 2.5. Bitumen Bond Strength Test configuration [58]

Researchers have found this to be an effective test method for capturing the effect of moisture on asphalt binder-aggregate bond strength [59-60]. In this method, the effect of moisture is dependent upon the selected pair of aggregate and asphalt binder, which further highlights the dependence of aggregate and asphalt binder surface energy on the bond strength [59].

Test on Compacted Asphalt Mixtures.

Immersion-Compression Test: The test method is followed as per AASHTO T 165 “Standard Method of Test for Effect of Water on Compressive Strength of Compacted Bituminous Mixture [8]” and is used to evaluate the moisture sensitive of asphalt mixtures. The test method measures the loss of compressive strength due to intrusion of moisture on compacted asphalt mixtures. An Index of retained strength is calculated as a measure of moisture damage.

Index of retained strength, % = $\left(\frac{S_{conditioned}}{S_{unconditioned}}\right) * 100$

Where,

$S_{unconditioned}$ = compressive strength of dry specimen, and

$S_{conditioned}$ = compressive strength of wet specimen.

The wet specimens included conditioning of the asphalt mixtures at 60°C for 24 hours, then later the specimens were transferred to a 25°C water bath for 2 hours after testing. The method includes testing of 4*4-inch cylindrical specimens (prepared using ASTM 1074) at 25°C under constant compressive deformation rates ranging from 0.2 to 2.0 inches per minute. Researchers have highlighted the lower reliability of this test method in predicting moisture sensitivity of the asphalt mixtures [54-55]. The Immersion-Compression test is ineffective for predicting moisture sensitivity of the asphalt mixtures [54].

The Modified Lottman Test: AASHTO T 283 [9] "Standard Test Method for Resistance of Compacted Bituminous Mixture to Moisture Induced Moisture Damage" is one of the most common test methods among the state highway agencies and asphalt contractors to predict moisture sensitivity of the asphalt mixtures. [16]. The test method concentrates on capturing the effect of moisture damage on diametric strength on the asphalt mixtures as a measure of fatigue and thermal cracking [61]. The procedure requires two groups of asphalt mixture specimens, conditioned (wet) and unconditioned (dry), inducing the combined effect on moisture and thermal cycles in asphalt pavements by inclusion of freeze-thaw conditioning [57]. The test procedure includes partial saturation (55% to 80%) of the asphalt specimens by applying a vacuum pressure of 26in Hg. The saturated specimens are subjected first to -18°C for a minimum of 16 hours, later to a 60°C water bath for 24 hours, and transferred to 25°C water bath for 2 hours before testing. The test procedure includes testing of cylindrical specimens of either 150mm diameter by 95mm thickness or 100mm diameter by 63.5mm thickness using an indirect mode of tensile strength testing. A compressive load at a constant deformation rate of 50mm/min along the vertical diametrical plane of the specimen is uniformly distributed through a 13mm curved-steel loading which splits the specimen along the plane of loading. This type of loading provides an equal distribution of tensile stresses perpendicular to the plane of loading [57]

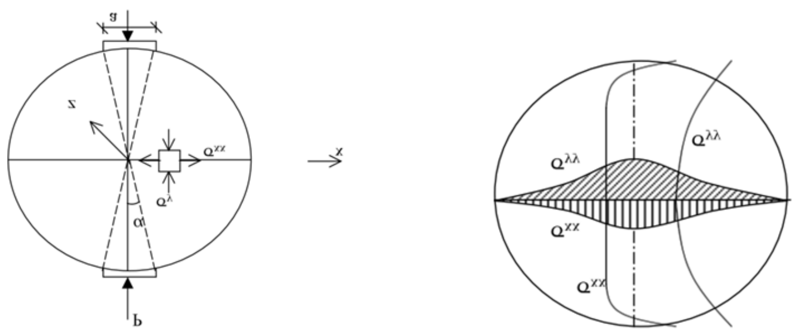

Figure 2.6. Shows a schematic of Indirect mode of tensile strength; a) Load configuration and b) stress distribution [57].

The indirect tensile strength (σ_{xx}) of the specimens is computed as:

$$S_t = \frac{2*P}{\pi*t*D},$$

where

S_t= indirect tensile strength (psi),

P= maximum load (lbf),

t= specimen height (in),

D=specimen diameter(in),

Over the years, numerous researchers have investigated the ability of the modified Lottman test to predict moisture sensitivity of the asphalt mixtures. A NCHRP study evaluated five different asphalt mixtures of known field performance using the modified Lottman test and did not find a satisfactory correlation with observed laboratory performance [1]. Kandhal and Rickards (2002) recommended the use of a cyclic loading test for moisture damage evaluation as it can simulate the pumping action of traffic [16]. Further, a NCHRP study in 2010 [62] conducted an interlaboratory study to investigate the precision estimates of the test and reported several shortcomings of the test method by analyzing the specimens via X-ray tomography images. The researchers highlighted the variability of the test results which may arise from the variable void structure, specimen geometry, and compaction method used for preparation of the specimens. Moreover, Kandhal and Rickards (2002) recommended a higher level of saturation (>90%) or inclusion of multiple freeze-thaw cycles for creating stripping effect. In contrast to that, Apeagyei et al. (2006) [61] stated that the use of plane stress analysis in calculating the tensile strength of the asphalt mixtures might cause erroneous results. The researchers reported that the presence of excessive moisture damage could lead to substantial plastic deformation or punching shear and redistribution of stresses under the loading strip, which can further account for inconsistent test results [61].

Moisture-induced Stress Tester (M.i.S.T) Device: ASTM D 7870 [21] “Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimen by Using Hydrostatic Pore Pressure” is characterized as a test producer performed by MiST device (shown in figure 2.7). The test procedure applies alternating hydraulic pressure and vacuum cycles to asphalt mixture specimens to simulate the effect of hydraulic scoring. The specimens placed in the water-filled MiST device chamber are subjected to two consecutive cycles, the first cycle includes keeping the specimens for 20hrs at 60°C to represent adhesion failure. Following the adhesion cycle a cohesion failure was simulated by applying 3500 pressure cycles of 40psi at 60°C.

Figure 2.7. Moisture induced Stress Tester.

Loaded Wheel Tester Test (LWT): The Hamburg-loaded wheel tracking device manufactured by Helmut-Wind, Inc. of Hamburg, Germany was brought to the United States in 1990’s [15]. AASHTO standardize the test method as T 324 [10] “Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)”. The use of the LWT for moisture sensitivity evaluation is based on pass/fail criteria using different parameters. Parameters obtained from LWT results for the evaluation of moisture sensitivity resistance include post compaction consolidation, creep slope, stripping slope, maximum rut depth (i.e., 12.5 mm), passes at maximum rut depth, and stripping inflection point (SIP) [10]. Post compaction consolidation is the rut depth at 1000 passes. Creep slope characterizes the inverse of deformation rate in the plot of creep phase of the rut depth versus number of wheel passes. The creep phase starts after the post-compaction consolidation phase and ends before stripping occurs. There is a steady increase in deformation in the creep phase due to viscous flow [17]. Stripping slope is the inverse of the deformation rate at points where rut depth increases rapidly as moisture damage occurs. A mixture with a larger stripping slope value is more susceptible to moisture damage. The ratio of the creep slope to the stripping slope has been used to characterize moisture sensitivity of asphalt mixtures in some states [63-64]. The SIP is the number of passes at the intersection of creep slope and stripping slope. SIP is an indication of moisture damage and represents the point where stripping initiates in a mixture [64]. Researchers [64-66] have established an excellent relationship between laboratory measured SIP and field moisture damage performance. Over the years, the test has been gaining popularity among the state highway agencies and uses a pass/fail criterion of different parameters obtained for the test as a measure of moisture sensitivity of asphalt mixtures [13]. However, some researchers have reported the limitations of the LWT to consistently relate laboratory performance of different asphalt mixture types to field performance [17-20]. Lu and Harvey studied the effectiveness of the LWT test by evaluating moisture susceptibility of polymer modified and conventional asphalt mixtures. The researchers observed that in conventional asphalt mixtures the LWT test overestimated the laboratory rutting performance as compared to field rutting performance. In addition, the LWT test was found to underestimate the laboratory rutting performance of polymer modified asphalt mixtures as compared to field rutting performance [17].

Induced moisture in asphalt pavements weakens the bond strength within the asphalt mixtures and causes a loss of stiffness in asphalt mixtures, which further leads to distresses such as fatigue cracking, rutting, stripping, and raveling [68]. The surface layer of asphalt pavements under saturated conditions are likely to exhibit rutting, as shear stress accumulate at the surface due to traffic loading. Further, a loss in cohesion within the asphalt pavements can lead to top-down cracking. Due to a decrease in rate of evaporation, asphalt pavement base layers retain moisture for a longer duration, this exacerbates the degradation of the asphalt pavements and can lead to onset of bottom-up fatigue cracking [40]. Different laboratory test methods have been developed over the years to evaluate the fracture resistance of asphalt mixtures. These test methods include the indirect tension (IDT) test (ASTM D 6931), bending beam fatigue (AASHTO T 321) test, Texas overlay test (Tex-248-F), the semi-circular bending test (ASTM D 8044), etc. Each of the above-mentioned tests offers some unique advantages and disadvantages [5,68,70].

The SCB test has been investigated over the years and has been found to relate laboratory cracking potential to field cracking performance consistently [68-72]. In recent years, researchers have also ranked the SCB high among other cracking test protocols due to the ease of test specimen preparation, its sensitivity to mix design variables, and quick testing time [16].

Semi-Circular Bend Test (SCB): The SCB test is a three-point bending test performed on a notched semi-circular asphalt mixture specimen. The pre-notching or crack initiation in the SCB test is based on the hypothesis that the energy stored at the fracture process zone (vicinity of the crack) is equal to the amount of energy required to form new surfaces [69]. The geometry of the SCB test allows crack propagation throughout the specimen by inducing tension at the bottom of the specimen [70]. The test method uses the critical strain energy release rate or the critical J-integral (J_C) to characterize the fracture resistance of asphalt mixtures. Figure 2.8 shows the loading configuration of the SCB test.

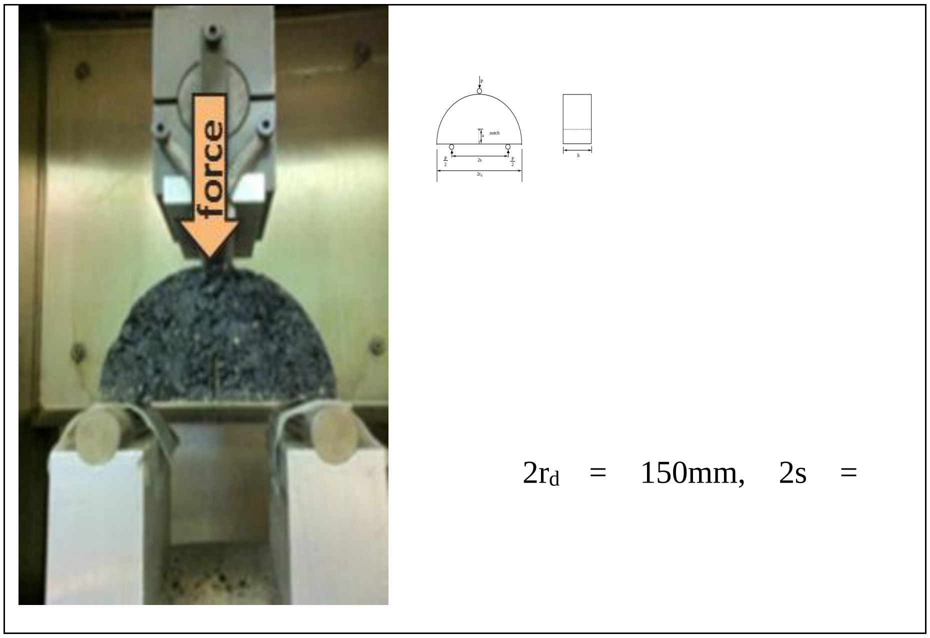

Figure 2.8. SCB Test Schematic

The SCB test geometry and the critical strain energy (Jc) approach was introduced in paving technology to characterize asphalt mixtures' resistance to fracture [70]. The researchers in the study employed asphalt mixtures using different asphalt binder types; crumb rubber modified (CRM), chemically modified crumb rubber (CMCB), and an unmodified asphalt binder; they reported an increase in fracture resistance with inclusion of crumb rubber. The study highlighted the potential of the SCB test to evaluate the fracture resistance of the asphalt mixtures using three notch depths (25.4, 31.8, and 38.0 mm). Moreover, Kim et al. (2012) [71] evaluated the potential of the SCB test to relate to filed cracking performance. The study utilized thirteen plant loose mixtures and evaluated the J_C corresponding to each mixture using a semi-circular specimen of 150mm diameter by 57mm thick at three different notch depths of

25.4, 31.8, and 38.0mm. The researchers found that the parameter J_c obtained from the SCB test corelates well (approximately 73%) with the field cracking performance of the asphalt mixtures obtained from the Louisiana Pavement Management System (PMS).

Ali et al. (2017) [72] used the SCB Jc parameter to capture moisture damage in asphalt mixtures by conditioning the mixtures in Moisture induced Stress Tester (MiST). The researchers observed a decrease in Jc as specimens were conditioned in the MiST. Despite the ability of the SCB to relate laboratory cracking potential to field cracking performance, limited research has been conducted on the potential of the test to evaluate moisture damage in asphalt mixtures [72].

CHAPTER 3. EXPERIMENTAL PROGRAM

3.1. Material Description

An unmodified PG 67-22 and a styrene-butadiene-styrene (SBS) polymer-modified PG 70-22 asphalt binder meeting Louisiana standard specifications were utilized (LADOTD 2016 [25]). Three aggregate types, limestone, crushed gravel, and semi-crushed gravel meeting Louisiana specification for 12.5 NMAS were used. It is noted that the limestone aggregate had lower absorption values (absorption<2%) and the crushed and semi-crushed gravel aggregates had higher absorption values (absorption >2%). The selected gradation of the semi-crushed gravel was such that all particles passing the 4.5 mm sieve size were crushed, whereas those retained on the 4.75 mm sieve size were smooth and round aggregates.

Figure 3.1 shows the three designed gradations used in this study with 12.5 mm NMAS. The mixtures used in the study were designed following the Louisiana specifications for roads and bridges manual, section 502 [25]. The crushed gravel gradation, which lies above the max-density line, represents the finer graded mixture as the percent aggregate passing the sieve size 2.36 mm (no.8 sieve) was more than 40% of the composite blend. The Limestone and Semi-Crushed Gravel represented coarse graded mixtures, as the percent aggregate passing the size 2.36 mm were less than 40%. Limestone and Semi-Crushed Gravel were graded similar to better understand the effect of aggregate absorption and angularity. The crushed gravel mixtures used more crushed and fine aggregates than semi-crushed gravel to evaluate the effect of aggregate angularity and mixture density.

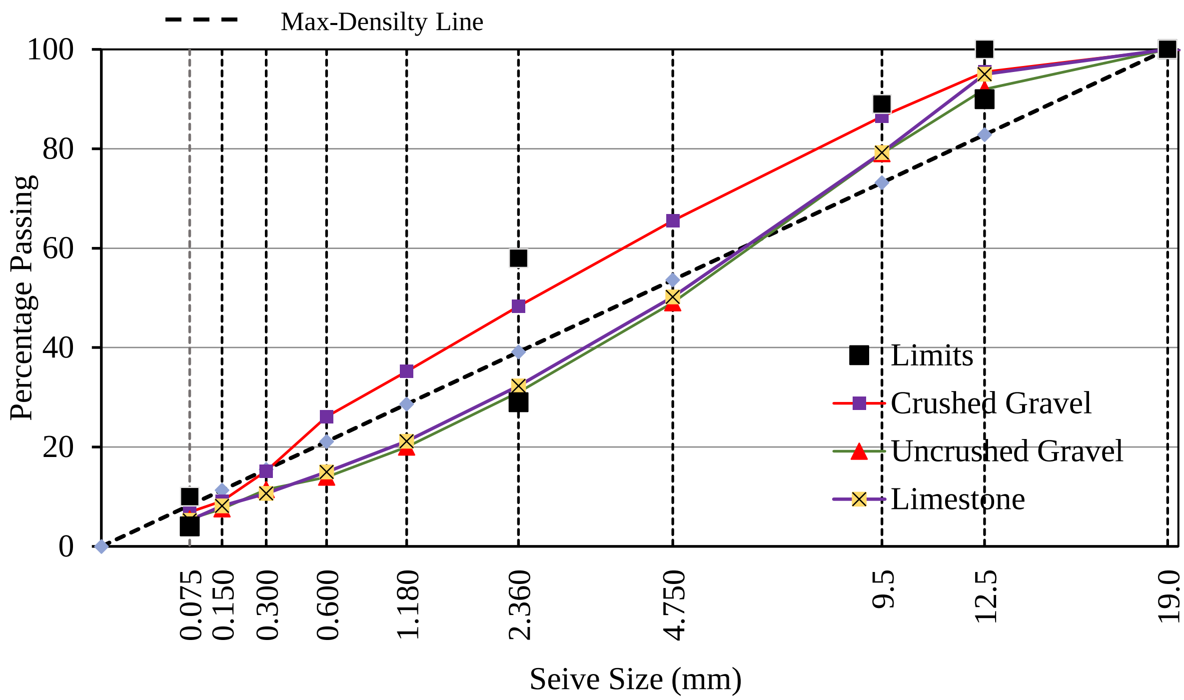

Figure 3.1. Asphalt Mixture Gradations

The asphalt binders obtained from the manufactures were verified meeting section 502 of the 2016 Louisiana Standard Specifications for Roads and Bridges Louisiana Specifications [44]. Table 3.1 list the tests the required specifications for grading of the asphalt mixtures along with the acceptable range of the specific property. An asphalt binder was graded following AASHTO T 315 [73], AASHTO T 240 [22], AASHTO T 51 [74], and AASHTO T 313 [75].

Table 3.1. Asphalt Binder Verification

Property	AASHTO TEST METHOD	LADOTD SPEC [44] PG 67-22[1]	PG 67-22[2]	LADOTD SPEC [44] PG 70-22[1]	PG 70-22[2]
Test On Original Binder					
Dynamic Shear, 10 rad/s, G*/sin Delta, kPa	AASHTO T 315 [61]	1.00+ @ 67°C	1.28	1.00+ @70°C	1.86
Test On RTFO residue, AASHTO 240 [53]					
Mass Loss, %	AASHTO T 240 [53]	1.00-	0.09	1.00-	0.08
Dynamic Shear, 10 rad/s, G*/sin Delta, kPa	AASHTO T 315 [61]	2.20+ @67°C	2.63	2.20+ ,@70°C	3.38
Ductility, 25°C, 5cm/min, cm	AASHTO T 51 [62]	90+	150	MSCR, 67°C, Jnr (3.2kPa), Meet Curve	Yes (1.85,38)
Test on PAV residue, R 28 [60]					
Dynamic Shear, @ 25°C, 10 rad/s, G*/sin Delta, kPa	AASHTO T 315 [61]	5000-	4700	6000-	5400
Bending Beam Creep Stiffness, S, MPa @ -12°C	AASHTO T 313 [63]	300-	230	300-	187
Bending Beam Creep slope, m-value @ -12°C		0.300+	0.311	0.300+	0.324
Delta Tc		N/A	-1.8	N/A	-1.3

[1] *Louisiana Standard Specifications for Roads and Bridges,2016 [44]; 2 Asphalt binder grades claimed by the manufacturer; N/A-Not Applicable*

3.2. Mixture Preparation

A total of seven 12.5 mm Superpave asphalt mixtures were utilized with two asphalt binder types and three aggregate types, refer to Table 3.2. A Level 2 design ($N_{initial}$ = 7, N_{design} = 65, N_{final} = 105 gyrations) was performed according to AASHTO R 35 [76], "Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)," AASHTO M 323, "Standard Specification for Superpave Volumetric Mix Design [27]," and Section 502 of the 2016 Louisiana Standard Specifications for Roads and Bridges [25]. The optimum asphalt cement content was determined based on volumetric properties (VTM = 2.5 – 4.5 %, VMA ≥ 13.5%, VFA = 69% -80%) and densification requirements (%G_{mm} at $N_{initial} \leq 90$, %G_{mm} at $N_{final} \leq 98$). Further, six mixtures (M1-M6) were laboratory produced and compacted, whereas mixture M7 was plant produced and laboratory compacted.

Mixtures M1, M2, and M3 included unmodified PG 67-22 asphalt binder and limestone, crushed gravel, and semi-crushed gravel aggregates, respectively, Table 3.2. Mixtures M4, M5, and M6 comprised of SBS modified PG 70-22 asphalt binder and limestone, crushed gravel, and semi-crushed gravel aggregates, respectively, Table 3.2. Mixture M7 was plant produced mixture prepared with unmodified PG 67-22 and Limestone aggregate. It is worth noting that mixture M7 contained liquid anti-strip additive (Arr-Maz Products, Inc) at a dosage rate of 0.6% by weight of the mixture, and 19% RAP material, Table 3.2. Table 3.3 lists the volumetrics and properties of the asphalt mixtures incorporated in the study.

Table 3.2. Asphalt Mixtures compositions

Mix ID	**Asphalt Binder Type**	**Aggregate Id:**	**ASA**	**RAP**	**Moisture Sensitivity**
M1	PG 67-22[1]	Limestone	N/A	N/A	Low
M2		Crushed Gravel	N/A	N/A	High
M3		Semi-Crushed Gravel	N/A	N/A	High
M4	PG 70-22[1]	Limestone	N/A	N/A	Low
M5		Crushed Gravel	N/A	N/A	High
M6		Semi-Crushed Gravel	N/A	N/A	High
M7	PG 67-22[1]	Limestone	0.6% (LA-2)	19%	Low

[1] *Meeting 2016 Louisiana DOTD specifications for Road and Bridges; RAP: Recycled asphalt pavement content; N/A: not applicable; LA-2: Liquid anti-strip additive; Low: low moisture susceptible aggregate (water absorption < 2%); High: high moisture susceptible aggregate (water absorption > 2%)*

Table 3.3. Asphalt Mixture properties and volumetrics

Property	Limestone (M1 and M4)	Crushed Gravel (M2 and M5)	Semi-Crushed Gravel (M3 and M6)	Limestone (M7)
NMAS	12.5 mm			
Gmm	2.502	2.383	2.361	2.479
AC (%)	4.9	4.7	5.6	5.1
% Gmm @ N_{ini}	88.1	89.2	87.9	88.9
%Gmm @ N_{max}	96.3	97.4	94.2	97.9
Air Voids (%)	4.0	3.8	3.5	3.7
VMA	14.0	13.9	13.9	13.9
VFA	71	74	75	74
Dust Ratio	0.9	1.0	1.1	1.1
P_{be} (%)	4.5	5.1	5.0	4.4
Absorption (%)	1.6	2.3	2.3	0.8
% passing 2.36mm	32	42	31	36

3.3. Material Characterization

Two experiments, asphalt binder and asphalt mixture experiments, were performed to achieve the objectives of this study. An unmodified PG 67-22 and a Styrene-butadiene-styrene SBS modified PG 70-22 asphalt binder were used in the asphalt binder experiments. Each asphalt binder type was subjected to five conditioning levels, which included short-term aging following rolling thin-film oven test (Control); single freeze thaw (FT-1)-; triple freeze-thaw (FT-3)-; MiST 3500; and MiST 7000 conditioning cycles. The rheological properties of the asphalt binders were evaluated by performing a frequency sweep test at multiple temperatures, and multiple stress creep recovery (MSCR) test at 67°C.

3.3.1. Asphalt Binders Experiment:

In the asphalt binder experiment, asphalt binder specimens were subjected to five levels of moisture conditioning followed by the rheological characterization of the conditioned asphalt binders.

Moisture Conditioning of Asphalt Binders

Five conditioning levels were considered in the asphalt binder experiment. The first conditioning level (i.e., control) consisted of short-term aging of asphalt binder in accordance with the RTFO aging protocol, AASHTO T 240 [22]. For the remaining four levels of conditioning, RTFO aged asphalt binder was poured into a PAV pan to achieve a uniform thickness of 3.2mm. Then, the specimens in the PAV pans were subjected to single freeze-thaw- (FT-1), triple- freeze-thaw- (FT-3), MiST 3500- and MiST 7000 conditioning cycles for the second, third, fourth, and fifth conditioning levels, respectively. A detailed description of the Freeze-Thaw and MiST conditioning levels is provided in the asphalt mixture experiment section.

Rheological Characterization

The Dynamic Shear Rheometer (DSR) was used to evaluate the rheological properties A Frequency sweep at multiple temperatures and frequencies and Multiple Stress Creep Recovery (MSCR) tests were performed on asphalt binders subjected to the five conditioning levels. A minimum of three replicates were used in each test. For the MSCR test, a new parameter, $J_{nrslope}$, was computed to capture the stress sensitive characteristics of the asphalt binder due to moisture conditioning [77]. This parameter ensured that the asphalt binder does not fail under real-world application of high stresses and temperatures and demonstrated a good correlation of the parameter with the incremental change in field rut depth. A lower $J_{nr\text{-}slope}$ value is desired and is an indication of better stress sensitivity [78]. The parameter was determined as shown below:

$$J_{nr-slope} = \frac{dJ_{nr}}{d\tau} \times 100$$

Where,

dJ_{nr} = difference in Jnr values at 0.1 and 3.2 kPa stress levels

$d\tau$ = difference between higher (3.2 kPa) and lower stress levels (0.1 kPa)

3.3.2. Asphalt Mixture Experiment

In the asphalt mixture experiment, asphalt mixture specimens were subjected to five levels of moisture conditioning followed by the mechanical characterization of the conditioned asphalt binders.

Moisture Conditioning of Asphalt Binders

Five conditioning levels were considered in the asphalt mixture experiment. The first conditioning level (i.e., control) consisted of short-term aging of loose asphalt mixture samples following "Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA), ASTM R 30" prior to compaction in the gyratory compactor. The other four conditioning levels were performed on compacted asphalt mixtures specimens as discussed below:

Freeze-Thaw Conditioning: The freeze-thaw conditioning was performed in accordance with AASHTO T 283 [9], "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage." For the second and third conditioning levels, RTFO aged asphalt binders and compacted short-term aged asphalt mixture samples were subjected to single and triple freeze-thaw conditioning cycles, respectively. For each conditioning level, asphalt mixture specimens were partially vacuum saturated to levels between 70% and 80%. Vacuum-saturated specimens were covered tightly with plastic wraps and placed in a freezer at a temperature of 18ºC for 16 hrs. Next, the asphalt mixture specimens were removed from the freezer and placed in a water bath at 60ºC for 24 hours. Asphalt binder specimens were conditioned without vacuum saturation or utilizing plastic wraps. It is worth noting that for the three conditioning cycles, specimens were removed from the 60°C water bath, tightly covered with plastic wraps, and then placed back in the freezer to repeat freeze-thaw cycles two more times. After conditioning, the specimens were removed from a 60ºC water bath and placed in another water bath at 25ºC before testing.

MiST Conditioning: The moisture-induced stress tester (MiST) conditioning was performed according to "Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure (ASTM D 7870 [21])." For the fourth and fifth conditioning levels, RTFO aged and compacted asphalt mixture samples were conditioned at 3500 and 7000 cycles, respectively, in the MiST. Specimens were placed in the MiST and the chamber was filled with water to the appropriate level. The specimens were kept in the machine at 60ºC for 20 hours to simulate adhesive failure in the mixture. Then, a pressure amplitude of 40 psi was applied for 3500 and 7000 cycles, respectively, for the fourth and fifth conditioning levels. After conditioning, the specimens were removed from the MiST and placed in another water bath at 25ºC before testing.

Asphalt Mixture Mechanical Evaluation

Loaded Wheel Tester (LWT): The Loaded Wheel Tracking (LWT) test was conducted following AASHTO T 324 "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt [10]." The test is considered a torture test, which produces damage by rolling a 703 N (158 lb.) steel wheel across the surface of Superpave gyratory compacted specimens (150mm diameter by 60mm thick) that are submerged in water at 50°C for a maximum of 20,000 passes.

In this study, the average rut depth at 20,000 passes was used in the analysis. A minimum of four replicates was used in each test.

Modified Lottman Test: The modified Lottman test was conducted in accordance with AASHTO T 283 "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage [9]." The test consisted of the freeze-thaw conditioning cycle and subsequent indirect tensile strength (ITS) test to determine the effect of moisture conditioning on mixture indirect tensile strength. The procedure uses two sets of specimens compacted to 150-mm in diameter and 95-mm in thickness at 7.0±0.5% air void. These two sets included the control set without condition and the conditioned set with partial vacuum saturation and a freeze-thaw cycle (single or triple). A split tensile test at 25°C was performed on each set of specimens, and the tensile strength ratio (TSR), which is the ratio of the indirect tensile strength of the conditioned samples to that of the control set, was determined as a measure of moisture damage. A minimum of three replicates was utilized at each conditioning level.

Semi-Circular Bending (SCB) Test: The SCB test was performed per ASTM D 8044 "Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures [34]." This test was performed to characterize the fracture resistance of asphalt mixtures regarding the critical strain energy release rate or the critical J-integral (Jc). To determine Jc, specimens with three notch depths (i.e., 25.4, 38.1, and 38 mm) were considered. A minimum of four replicates were tested for each notch depth at 25°C. The SCB specimens were loaded monotonically at a constant crosshead displacement of 0.5mm/min until failure. The load and deformation data were recorded continuously for the determination of Jc

[68]. A Higher Jc value is an indication of higher cracking resistance at intermediate-temperatures and vice versa.

In this study, a new parameter (J_d) was evaluated to quantify the effect of moisture damage (adhesive and cohesive failure) on the cracking resistance of asphalt mixtures. Moisture damage in asphalt is a cumulative effect of reduction in strength and stiffness due to cohesive and adhesive failure [4]. The J_d parameter was evaluated to capture the effect of moisture damage on reduced tensile strength (lower peak load in the SCB test) and reduced stiffness of asphalt binder film (increased deformations in SCB test) of asphalt mixtures. The stain energy was normalized by the displacement at peak load, and the J_d parameter was determined, as shown below:

$$J_d = -\left(\frac{1}{B}\right)\left(\frac{dU_d}{da}\right)$$

where,

J_d = critical strain energy per unit peak deformation (kJ/mm3),

B = specimen thickness (mm),

a = notch depth (mm), and

U_d = peak strain energy per unit peak deformation (N.mm/mm).

Then the J_d ratio was computed as shown below:

$$J_d\text{-ratio} = J_{d\_Conditioned} / J_{d\_Control}$$

Where,

$J_{d\_Conditioned}$ = J_d value of the conditioned level of an asphalt mixture, and

$J_{d\_Control}$ = J_d value of the control level of the asphalt mixture.

CHAPTER 4. RESULTS AND ANALYSIS

This chapter presents the results and analysis of the asphalt binder and asphalt mixture experiments employed in the study. The analysis of the results was performed using mathematical tools, as mentioned in section 1.5 of the report. Further, the results are compared based on their statistical inference and have been referred to as A, B, C, D, and E.

4.1. Asphalt Binder Evaluation

Rheological characterization of conditioned asphalt binder was performed using frequency sweep test and MSCR. The results are listed below.

4.1.1. Frequency Sweep

Effect of conditioning on asphalt binder stiffness

Figure 4.1 and 4.2. shows master curves and average rut factor ($G^*/\sin(\delta)$, $_{50°C,\ 10\ rad/s}$) values obtained from frequency sweep test results for asphalt binders evaluated. For the both the asphalt binders, the effect of freeze-thaw (FT-1 and FT-3) and MiST (MiST 3500 and MiST 7000) conditioning resulted in an increase in dynamic modulus values (increased stiffness) as compared to the RTFO. It is worth noting that the unmodified PG 67-22 asphalt binder showed higher increase in stiffness from RTFO for each conditioning level as compared to the SBS modified PG 70-22. Furthermore, with progressive moisture damage i.e., from FT-1 to FT-3 or from MiST 3500 to MiST 7000, each asphalt binder resulted in an increase in stiffness.

The rut factor ($G^*/\sin(\delta)$, 50°C, 10 rad/s) was computed to evaluate the effect of moisture conditioning on the rutting performance of the asphalt binders evaluated [32]. For PG 67-22 asphalt binder, an increase in rut factor was observed with the freeze-thaw conditioning (FT-1 and FT-3) conditioning when compared to RTFO, Figure 4.1. Whereas the MiST conditioning (MIST 3500 and MiST 7000) had a minimal effect on rut factor values. Further, for PG 70-22 asphalt binder, freeze-thaw and MiST conditioning had minimal effect on the rut factor values, Figure 2b. This observation attributes to the use of SBS modified PG 70-22 asphalt binder for better moisture resistance. Moreover, increased stiffness and rut factor values observed with PG 67-22 have the potential to improve high-temperature performance and moisture damage resistance [57].

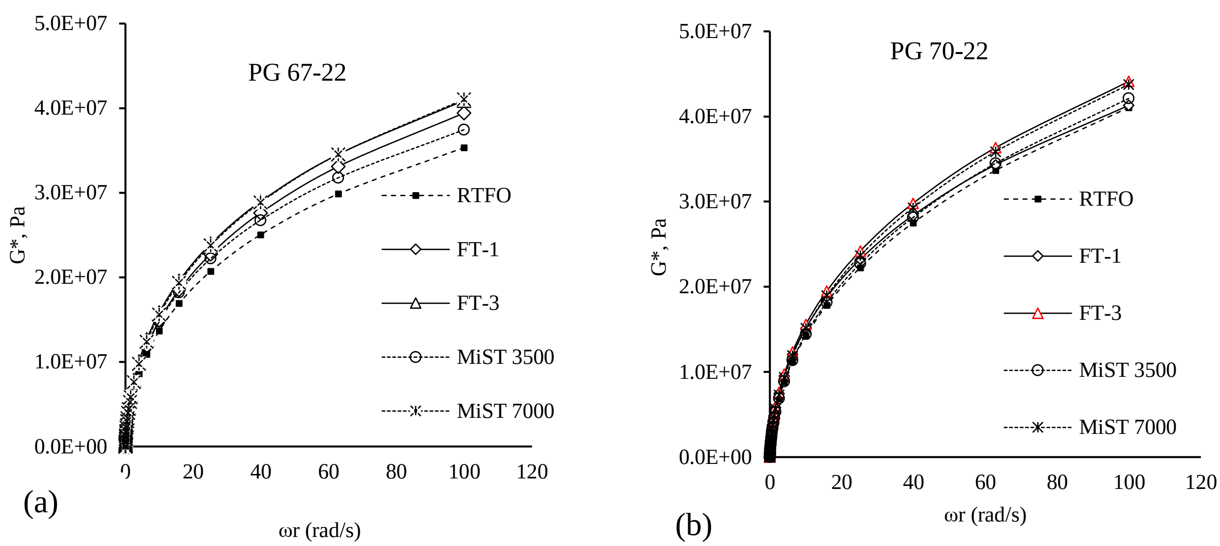

Figure 4.1. Master Curves form Frequency Sweep Test for: a) PG 67-22 and b) PG 70-22

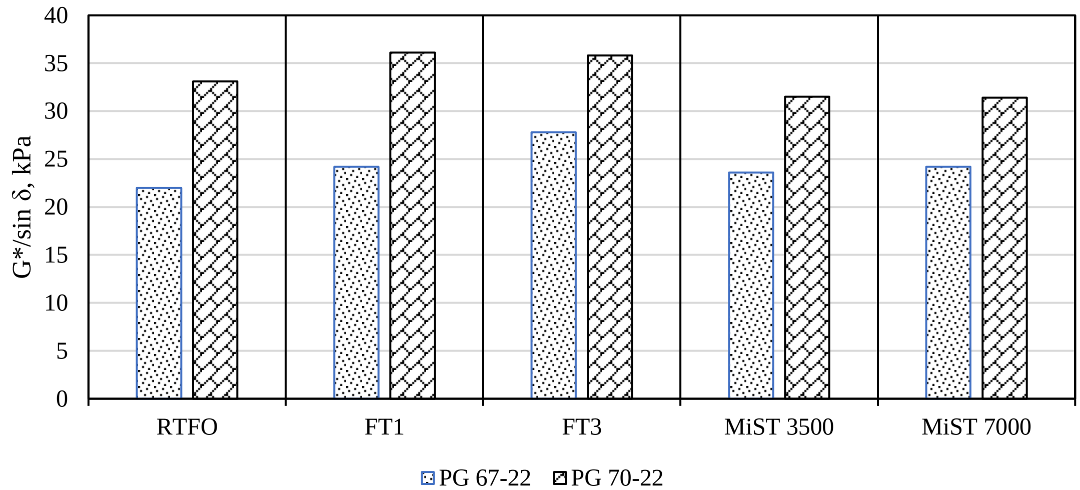

Figure 4.2. Rut factor (G*/sin(δ) at 50°C and 5Hz

4.1.2. MSCR

*Effect of conditioning on elastic response of asphalt binder*s

Figures 4.3a and 4.3b show Jnr and percent recovery (R) at stress level of 3.2 kPa for asphalt binders evaluated. For the asphalt binders evaluated, FT-1 and FT-3 conditionings resulted in a minimal Jnr decrease and R increase as compared to RTFO conditioned asphalt binder. Similar trend was observed for MiST 3500 and MiST 7000 conditionings.

Figure 4.3c presents the average Jnr slope values of asphalt binders evaluated. For the PG 67-22 asphalt binders, freeze-thaw conditioning (FT-1, and FT-3) resulted in a slight reduction in the asphalt binder's stress sensitivity compared to the control RTFO asphalt binder. However, MiST conditioning (MiST 3500, and MiST 7000) had no effect on the stress sensitivity of the asphalt binder as compared to the control RTFO asphalt binder. Freeze-thaw (FT-1, and FT-3) conditioning of the PG 70-22 to asphalt binder resulted in a slight reduction in the stress sensitivity of the asphalt binder as compared to the control asphalt binder. A similar reduction from RTFO was observed for the MiST conditioned PG 70-22 asphalt binder. The slight reduction in the stress sensitivity associated with the freeze-thaw and MiST conditioning of asphalt binders may be attributed to the increased stiffness observed in the frequency sweep test. The increase in stiffness has the potential to improve rutting and high-temperature performance [61].

Figure 4.4 presents the elastic response curve for the asphalt binders evaluated. Two clusters for each binder type were identified: PG 70-22 in the passing zone and PG 67-22 in the failed zone. For the two clusters of asphalt binders in Figure 4.4, freeze-thaw (FT-1 and FT-3) and MiST (MiST 3500 and MiST 7000) conditioning had no effect on the capability of the asphalt binder to meet the delayed elastic response criteria [44].

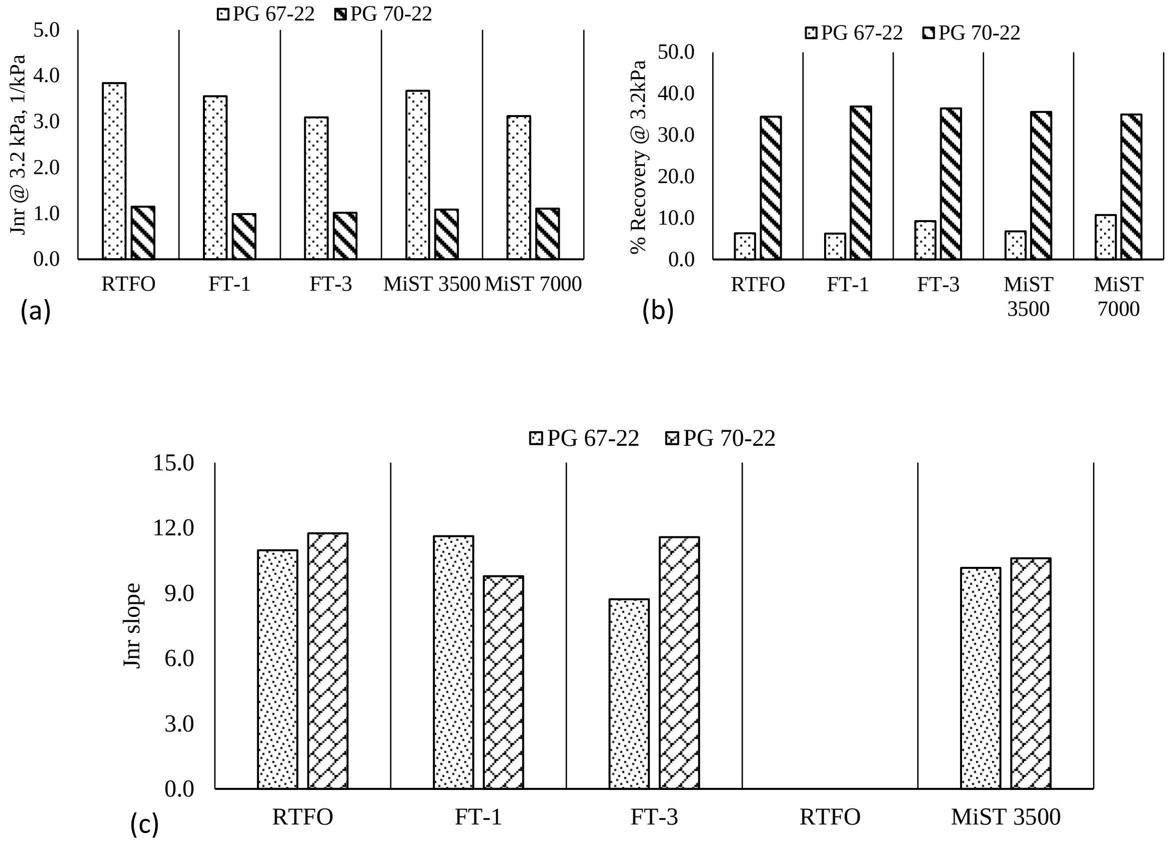

Figure 4.3. MSCR Test Results: a) Jnr_3.2 kPa, b) % recovery_3.2kPa, and c) Jnr slope

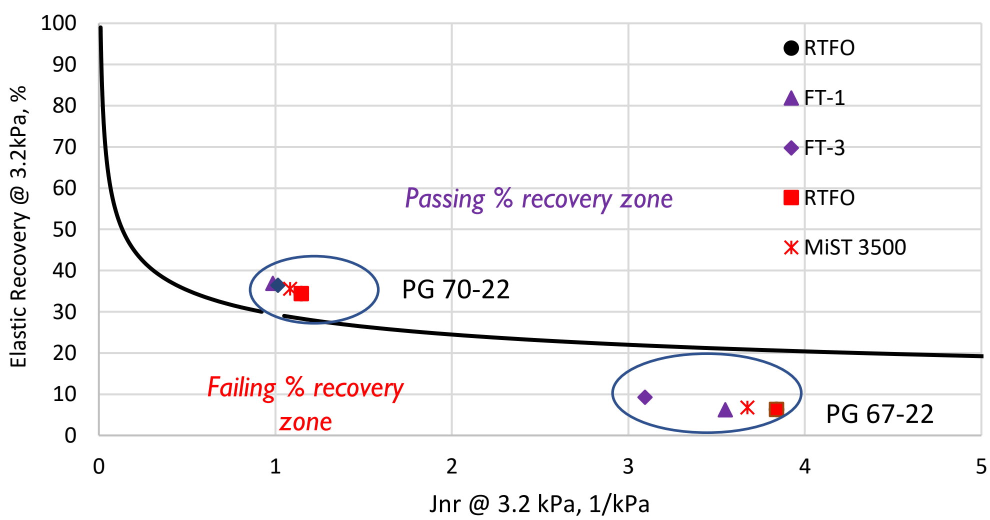

Figure 4.4. MSCR Test Results: Jnr vs elastic recovery plot

4.2. Asphalt Mixture Evaluation

4.2.1. Boil test

The current test practice involves boiling of loose asphalt mixtures for 10 minutes. After 10 minutes the asphalt mixtures were evaluated, and no visual stripping was observed. The study utilized three progressive time intervals (30mins, 60mins, and 120mins) to capture the effectiveness of the test method in predicting moisture susceptible asphalt mixtures.

Effect of asphalt binder type on percent AC loss

Table 4.1 presents the visually observed percent AC loss of asphalt mixtures evaluated using the boil test (ASTM D 3625) for various time intervals. As expected, all asphalt mixture showed an increase in stripping (% AC loss) with an increase in boiling time. PG 67-22 asphalt mixtures (M1 to M3) showed more stripping than PG 70-22 asphalt mixtures (M4 to M6) at every time interval. This observation attributes the use of SBS polymer modified asphalt binder which helps to resist the moisture damage. Moreover, mixture M7 exhibited less moisture damage as compared to M1 due to addition of anti-strip agents in mixture M7.

Effect of aggregate type on percent AC loss

Among PG 67-22 asphalt mixtures, mixtures M2 and M3 consist of high absorption aggregates (> 2%) and are characterized as moisture-sensitive asphalt mixtures compared to mixture M1 with low absorption aggregate (< 2%). Moreover, mixture M1 and M2 uses high angularity aggregates, whereas mixture M3 includes 50% of round and smooth aggregates. A trend in moisture resistance was observed where limestone mixtures were more moisture resistant than Crushed Gravel, which was more moisture resistant than Semi-crushed gravel (Table 4.2.1), which highlights the effect of moisture on angularity and absorption of the aggregates on moisture resistance.

Table 4.1. Percent AC loss in Asphalt Mixtures after 10,30, 60, and 120mins

Mixture Type	10min	30 mins	60mins	120mins
M1	2	5	13	18
M2	2	5	17	21
M3	2	8	21	32
M4	2	2	4	7
M5	2	3	7	10
M6	2	3	7	11
M7	2	3	6	10

4.2.2. Asphalt Colorimeter Tester (ACT)

Effect of asphalt binder type on percent AC loss

Table 4.2 presents the Sample Ranking Index (SRI) calculated using ACT on loose asphalt mixtures which had undergone the boil test for 10, 30, 60, and 120min. ASTM D 3625 visually suspects moisture damage in asphalt mixtures, whereas ACT uses a colorimeter to measure the change in color which occurs after subjecting loose mixtures to the boil test, as discussed in chapter 3. PG 67-22 asphalt mixtures (M1-M3) exhibited higher SRI than PG 70-22 asphalt mixtures, representing higher percent AC loss. This observation attributes the use of SBS polymer modified asphalt binder to help resist the moisture damage. Moreover, mixture M7 exhibited less moisture damage as compared to M1 due to addition of anti-strip agents in mixture M7.

Effect of aggregate type on percent AC loss

Mixture M2 and M3 consist of high absorption aggregates (> 2%) and are characterized as moisture-sensitive asphalt mixtures compared to mixture M1 with low absorption aggregate (< 2%). Moreover, mixture M1 and M2 uses high angularity aggregates, whereas mixture M3 includes 50% of round and smooth aggregates. A trend in moisture resistance was observed where limestone mixtures were more moisture resistant than Crushed Gravel, which was more moisture resistant than Semi-crushed gravel (Table 4.2), which highlights the effect of moisture on angularity and absorption of the aggregates on moisture resistance.

Table 4.2. Sample Ranking Index of boiled asphalt mixtures for 10, 30, 60, and 120mins

Mixture Type	**10mins**	**30 mins**	**60mins**	**120mins**
M1	1.2	2.0	2.7	3.7
M2	1.2	2.3	3.5	4.9
M3	1.4	2.7	4.1	6.4
M4	0.7	1.3	1.4	1.4
M5	0.8	1.2	1.4	1.7
M6	0.8	1.5	1.5	1.7
M7	1.0	1.4	1.7	1.9

4.2.3. Loaded Wheel Tracking (LWT) Test:

Effect of conditioning on rut depth @ 20,000 passes

Figure 4.5 represents the average rut depth for asphalt mixtures subjected to different conditioning levels. The effect of freeze-thaw (FT-1 and FT-3) and MiST conditioning (MiST 3500 and MiST 7000) on the asphalt mixtures evaluated caused a significant increase in moisture damage when compared to the control. Moreover, an increase in rut depth was observed with the progressive increase of freeze-thaw (from FT-1 to FT-3) and MiST conditioning (from MiST 3500 to MiST 7000).

MiST 3500 level resulted in significant higher moisture damage when compared to FT-1 for PG 67-22 asphalt mixtures (M1-M3). And for mixture M7, MiST 3500 and FT-1 had a similar effect, due to addition of anti-strip agent in M7. Whereas the effect of MiST 3500 and FT-1 on PG 70-22 asphalt mixtures were similar, but FT-3 and MiST 7000 affected them differently. These observations imply that the LWT has the capability of capturing the progressive moisture damage associated with different moisture conditioning levels.

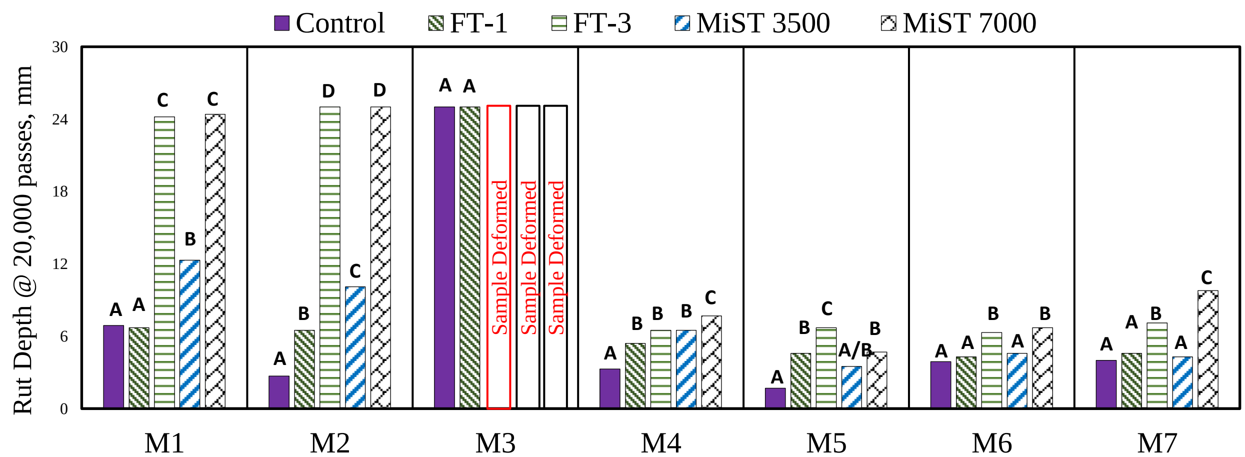

Figure 4.5. Effect of conditioning type on rut depth @ 20,000 passes

Effect of asphalt binder type on rut depth @ 20,000 passes

Figure 4.6 represents the effect of asphalt binder type on moisture resistance of: a) limestone; b) crushed gravel; and c) semi-crushed gravel aggregate. PG 70-22 asphalt binder mixtures (M4, M5, and M6) showed significant decrease in rut depth at all conditioning levels when compared to PG 67-22 asphalt mixtures (M1, M2, and M3) for all three aggregate types used in the study. It is interesting to note that PG 67-22 asphalt mixture caused extensive moisture damage with FT-3 and MiST 7000 levels. Mixture M1 exhibited max total rut depth (25mm) at 20,000 passes, mixture M2 reached test failure (max rut 25mm) before completion of 20,000 passes (Figure 4.8), and mixture M3 lost structural integrity during moisture conditioning levels (Figure 4.8c). Whereas, with the use of SBS-polymer modified asphalt binder, mixtures M4-M6 exhibited significant increase in moisture resistance. The inclusion of anti-strip agent in mixture M7 resulted in moisture resistant mixture when compared to mixture M1 with no anti-strip agent. These observations imply that the LWT test can capture the effects of different asphalt binder types (polymer modified and anti-strip additives).

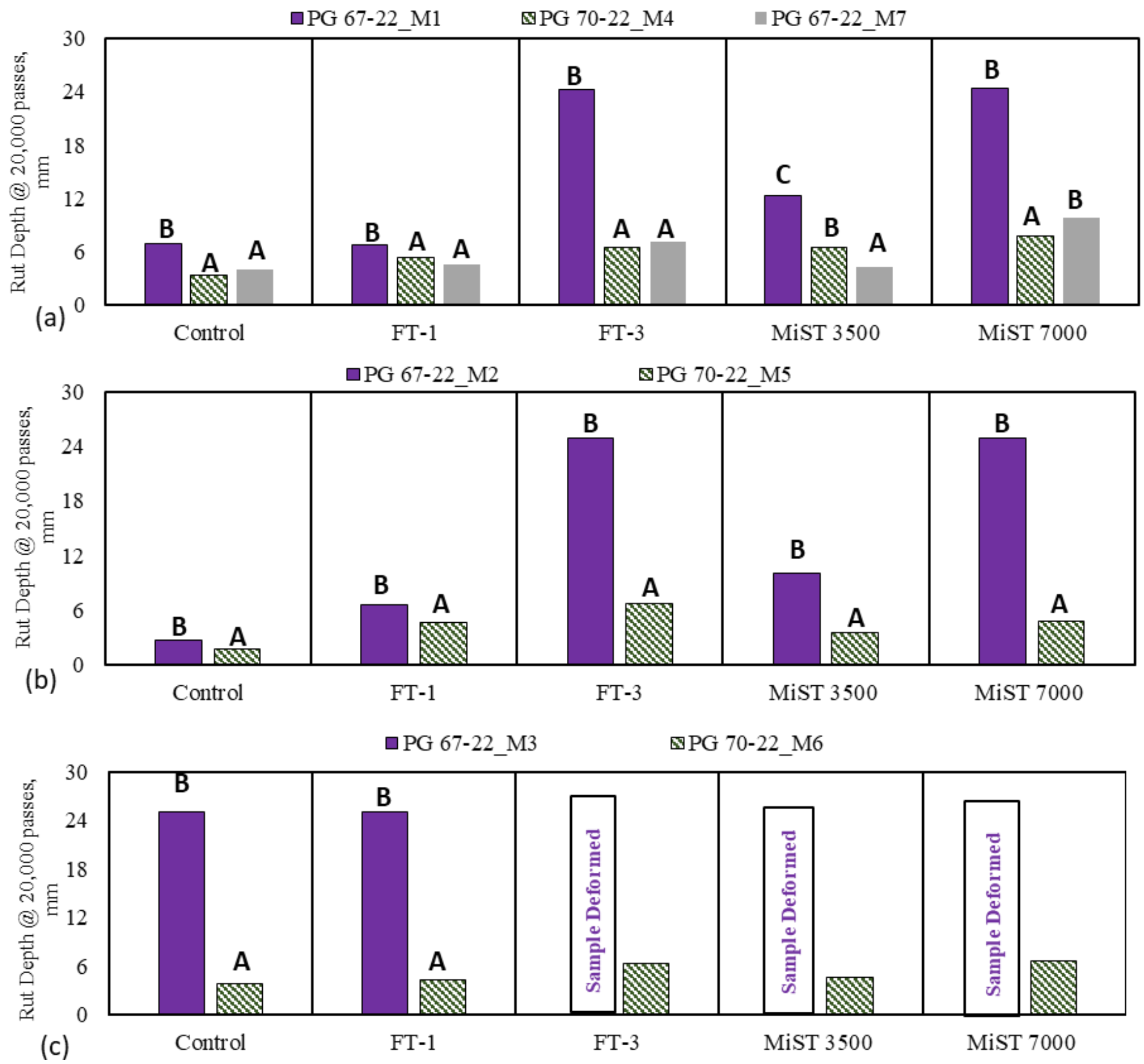

Figure 4.6. Effect of asphalt binder Type on Rut depth @ 20,000 passes on; (a) Limestone, (b) Crushed Gravel, and (c) Semi-crushed Gravel aggregate mixtures

Effect of aggregate type on rut depth @ 20,000 passes

Figure 4.7 presents the rut depth at 20,000 passes for different types of aggregates (Limestone, Crushed Gravel, and Semi-Crushed Gravel) with different asphalt binder types, specifically a-PG 67-22 and b-PG 70-22 used in the study. Figure 4.2.3a includes laboratory prepared PG 67-22 asphalt mixture (M1-M3) along with plant mixed-laboratory compacted asphalt mixture (M7), where Figure 4.8.b consists of PG 70-22 (M4-M6) asphalt mixtures. Among PG 67-22 asphalt mixtures, mixture M3 exhibited extensive moisture sensitivity (max rut 25mm before 20,000 passes) at the control level due to the use of 50 % round and smooth aggregates. Moreover, mixture M3 at severe moisture conditioning levels (FT-3, MiST 3500, and MiST 7000) exhibited a loss in structural integrity (Figure 4.8). Mixture M2 showed extensive moisture damage only at FT-3 and MiST 7000 level (figure 4.8) due to high absorption aggregates (> 2%) which was not highlighted at the control level. This observation highlights the need for including moisture conditioning with the LWT test to capture moisture sensitivity of asphalt mixtures.

A general trend of Limestone with anti-strip > Crushed Gravel > Limestone without anti-strip > Semi-Crushed gravel was observed with PG 67-22 asphalt mixtures. Among PG 70-22 asphalt mixtures (Figure 4.7b), the asphalt binder type (polymer-modified) dominated the effect of aggregate type. All three asphalt mixtures type behaved similarly with freeze-thaw conditioning (FT-1 and FT-3), whereas at MiST conditioning, Crushed gravel performed better than semi-crushed gravel and followed by limestone.

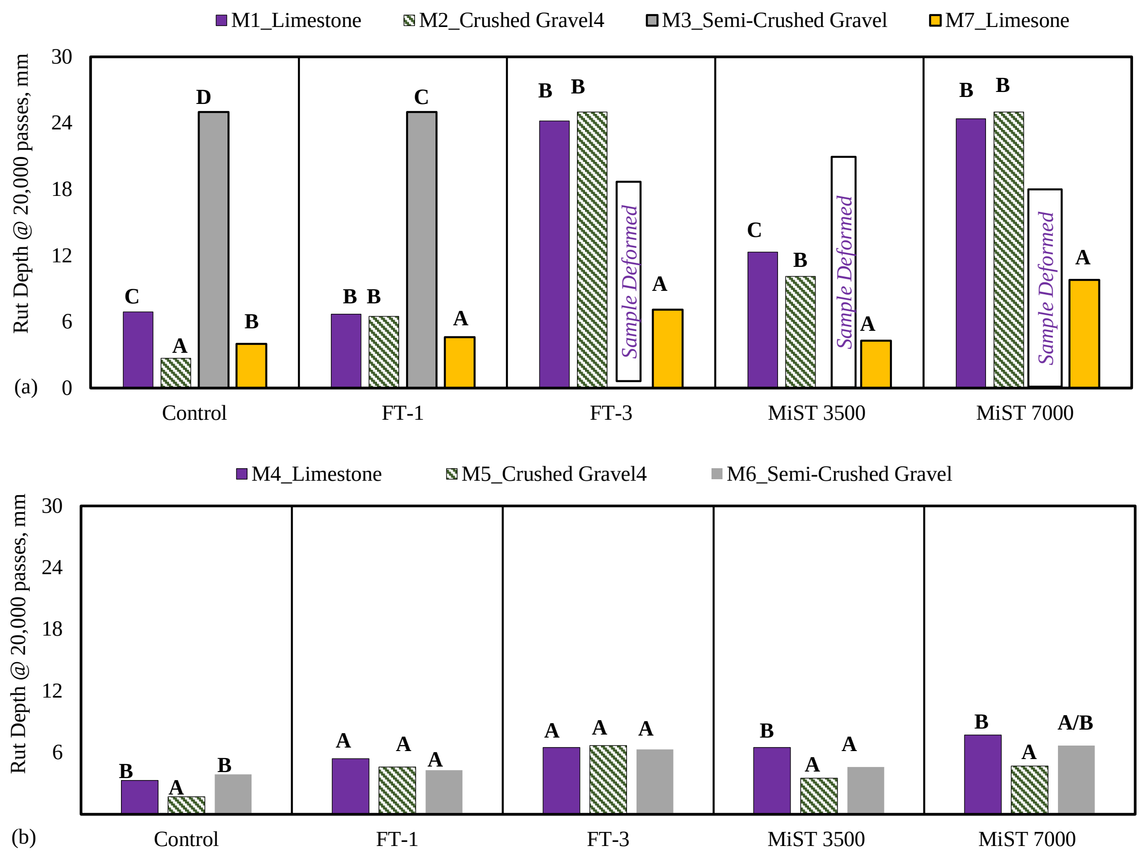

Figure 4.7. Effect of Aggregate Type on Rut Depth @ 20,000 passes of; (a) PG 67-22 and (b) PG 70-22 asphalt mixtures

Figure 4.8. Adhesive failure in M2 with a) FT-3 level, b) MiST 7000 level (left), and c) Loss in structural integrity in mixture M3

4.2.4. Modified Lottman Test:

Effect of conditioning on indirect tensile strength (ITS)

Figure 4.9 presents the average Indirect Tensile Strength (ITS) of the asphalt mixtures evaluated using the modified Lottman test. Freeze-thaw conditioning with a single cycle (FT-1) did not cause any significant change in ITS when compared to control for both PG 67-22 and PG 70-22 asphalt mixtures. Whereas with an increase in Freeze-thaw conditioning, i.e. form FT-1 to FT-3, a significant decrease in ITS among all asphalt mixtures was observed. Unlike the FT-1 conditioning level, the MiST 3500 level showed a significant decrease in ITS with PG 67-22 asphalt mixtures (M1-M3) and with high absorption PG 70-22 asphalt mixtures (M5 and M6). Moreover, the effect of MiST 3500 on mixture M7 was minimal due to the addition of an anti-strip agent. Whereas with an increase in MiST conditioning (MiST 3500 to MiST 7000) a significant decrease in ITS was observed only with mixture M4. Unlike the LWT test, the modified Lottman test is not able to capture the progressive moisture damage associated with moisture conditioning.

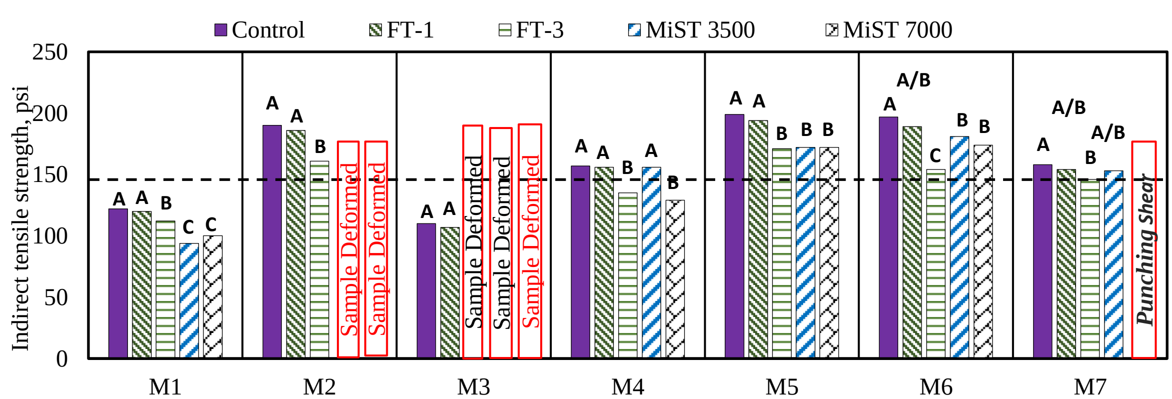

Figure 4.9. Effect of conditioning on Indirect Tensile Strength

<u>Effect of asphalt binder type on indirect tensile strength (ITS)</u>

The effect of the asphalt binder type on ITS with three different aggregates mixtures used in the study, (a) Limestone, (b) Crushed Gravel, and (c) Semi-Crushed Gravel is represented in Figure 4.10. A significant increase in ITS is observed with PG 70-22 asphalt mixture when compared to

PG 67-22 asphalt mixtures at all conditioned levels. Like the LWT test results (section 4.2.3), the modified Lottman test showed similar observations among PG 67-22 and PG 70-22 asphalt mixtures.

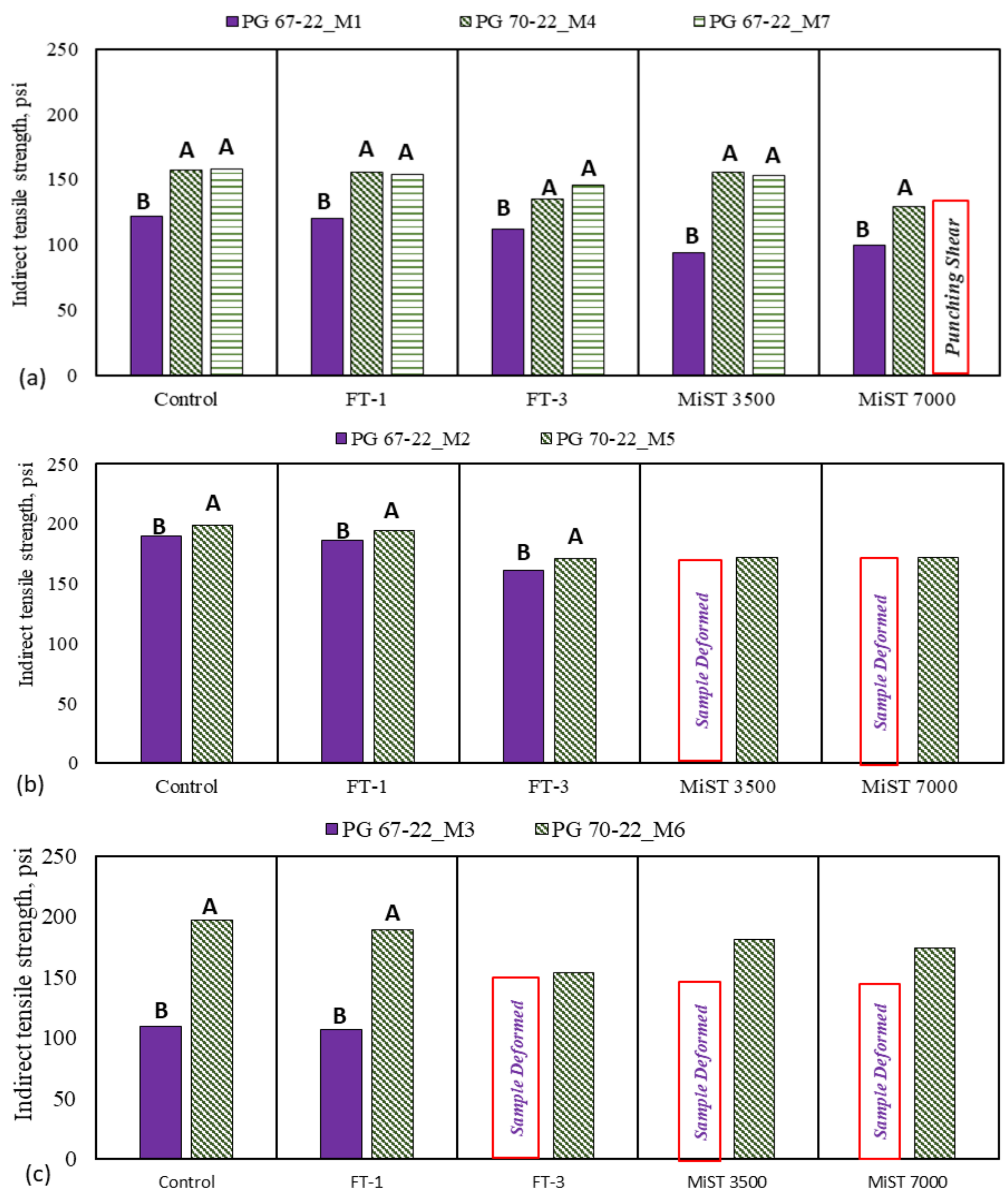

Figure 4.10. Effect of Asphalt Binder Type on Indirect Tensile Strength on; (a) Limestone, (b) Crushed Gravel, and (c) Semi-crushed Gravel aggregate mixtures

Effect of aggregate type on indirect tensile strength (ITS)

Figure 4.11 present the ITS for different types of aggregates (Limestone, Crushed Gravel, and Semi-Crushed Gravel) with PG 67-22 (figure 4.11a) and PG 70-22 (figure 4.11b). Unlike LWT test results, PG 67-22 asphalt mixtures showed a different trend in moisture damage observed with the modified Lottman test: Crushed gravel was more resistant to moisture damage than Limestone with anti-strip agent, which itself was more resistant than Limestone without anti-strip agent, which was more resistant than Semi-Crushed Gravel with Freeze-thaw conditioning. Like the LWT results, PG 67-22 asphalt mixtures exhibited extensive moisture damage with MiST conditioning (refer to section 4.2.3), mixture M2 exhibited change in geometry (Figure 4.8) whereas mixture M3 loses the structural integrity of the specimens (Figure 4.8). This observation highlights the extensive damage caused due to high absorption aggregates when compared to mixture M1 with low absorption aggregates. Further, the change in geometry of the mixture M2 specimens will lead to inconsistent test results, highlighting the limitation of the method in capturing extensive moisture damage. Furthermore, mixture M7 exhibited excessive plastic deformation under the loading strip (punching shear) as shown in Figure 4.12 which lead to inconsistent test results. The redistribution of the stresses under the loading strip due to excessive plastic deformation leads to additional stresses in the plane perpendicular to the loading plane, and has been listed as one of the shortcomings of the modified Lottman test [61]

Among PG 70-22 asphalt mixtures, the effect of aggregate angularity was highlighted at FT-3 level, as Semi-Crushed Gravel (M6) showed significantly lower ITS than Crushed Gravel (M5) due to inclusion of 50% round and smooth aggregates in M6. Similar to LWT test, the Crushed Gravel mixture exhibited higher ITS at all condition levels than Limestone mixture, as the Crushed Gravel is a fine graded mixture.

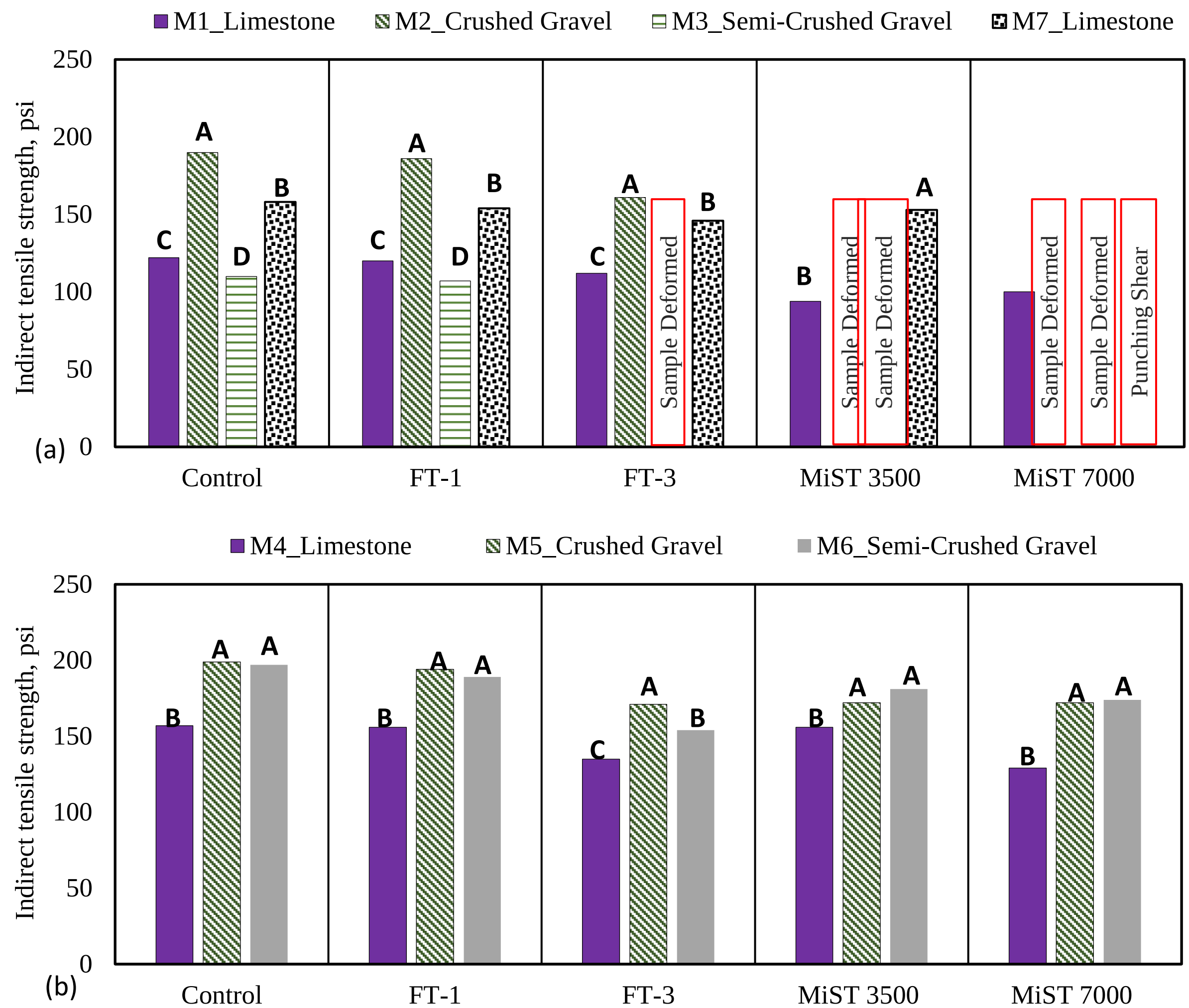

Figure 4.11. Effect of Aggregate Type on Indirect Tensile Strength of; a) PG 67-22 and b) PG 70-22 asphalt mixtures

Figure 4.12. Moisture damage in a) mixture M2 at MiST 3500, b) mixture M2 at MiST 7000, and c) mixture M7 at MiST 7000 (Punching Shear).

4.2.5. Semi-Circular Bend (SCB) Test:

Effect of conditioning on J_d-value

Figure 4.13 presents the J_d parameter computed from the load and displacement curves obtained from the evaluated asphalt mixtures. The effect of freeze-thaw and MiST conditioning caused a decrease in parameter J_d (cracking resistance) when compared to control. Further, with the progressive moisture damage i.e. either from FT-1 to FT-3 or from MiST 3500 to MiST 7000, a decrease in the J_d of the evaluated asphalt mixtures was observed. Mixture M2 and M3 with MiST conditioning exhibited sample deformation, as stated in section 4.2.4, and were unable to be evaluated. Like the LWT test, the SCB test has the potential to capture the incremental moisture damage associated with moisture conditioning levels.

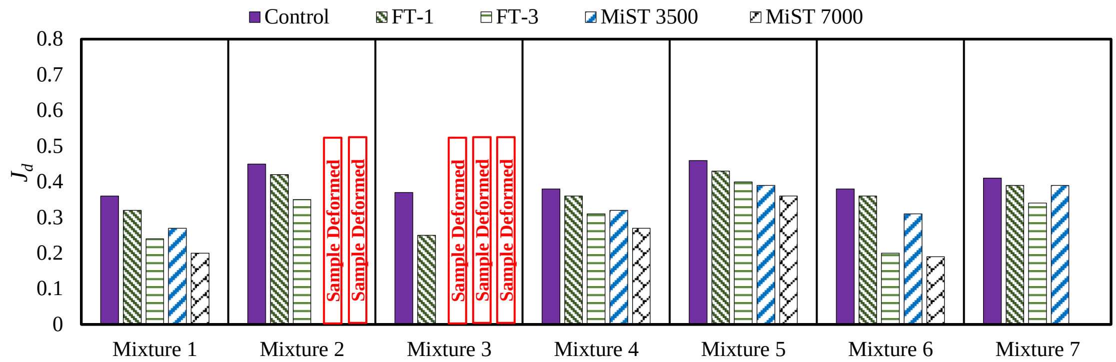

Figure 4.13. Effect of conditioning on SCB-Jd of asphalt mixtures

Effect of asphalt binder type on J_d-value

Figure 4.14 presents the effect of asphalt binder type on J_d – value (cracking resistance) at all conditioning levels with the three aggregates. An increase in J_d was observed with PG 70-22 asphalt mixture when compared to PG 67-22 asphalt mixtures at all conditioned levels. Further, mixture M7 showed better resistance to moisture damage than M1 at all condition levels due to the inclusion of an anti-strip agent (LA-2), figure 4.2.10a. Similar to modified Lottman test, mixture M2 at MiST 3500 and MiST 7000 level show a change in sample geometry due to use of high absorption aggregates. Furthermore, for mixture M3 at FT-3, MiST 3500, and MiST 7000 levels specimens lost structural integrity due to inclusion of 50% round and smooth aggregates. It is interesting to note that mixture M2 and M5 showed similar ITS value at the control and FT-1 level, a similar observation is reported by the SCB test.

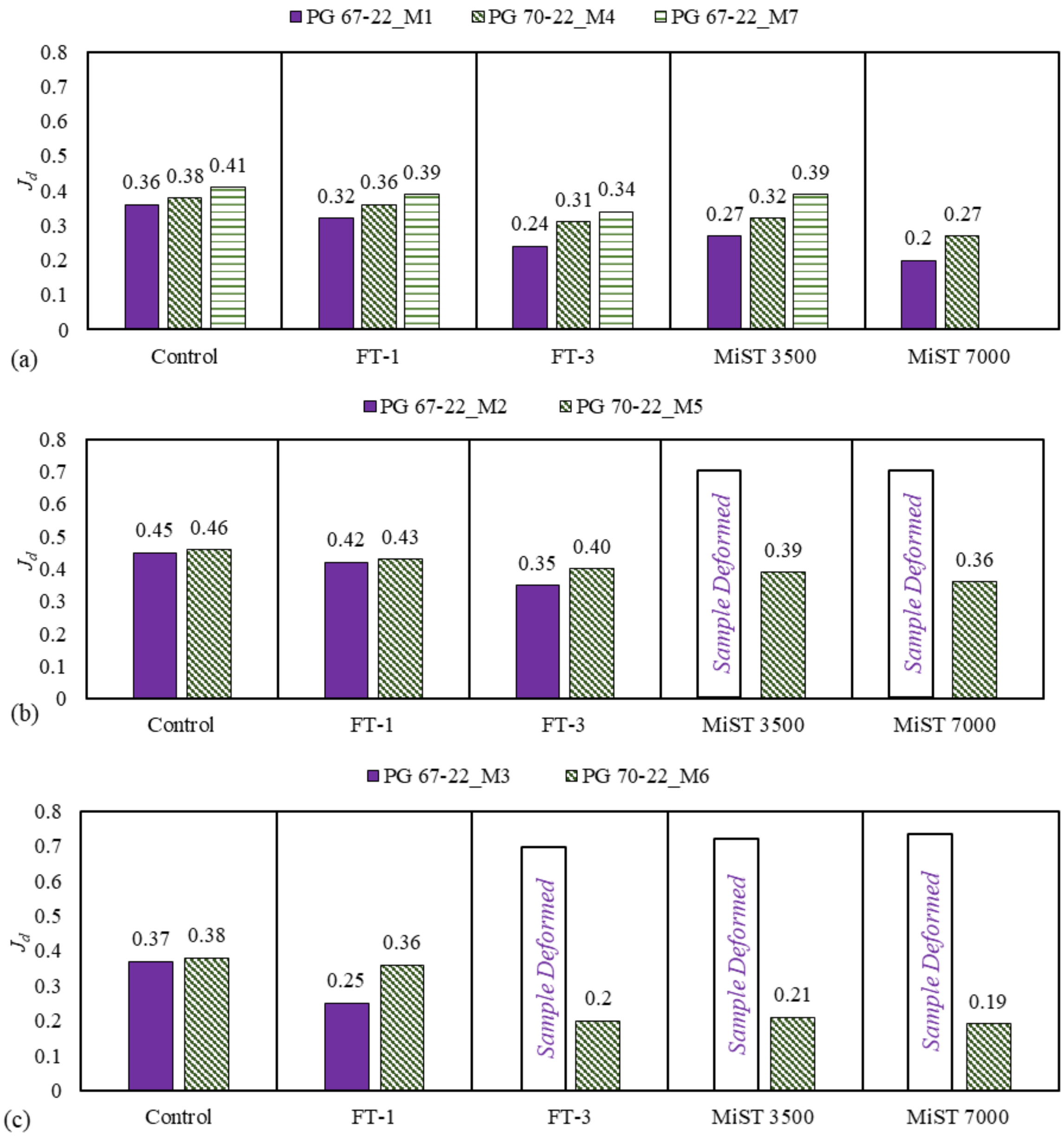

Figure 4.14. Effect of Asphalt Binder Type on SCB-Jd value on; a) Limestone, b) Crushed Gravel, and(c) Semi-Crushed Gravel aggregate mixtures

Effect of aggregate type on J_d-value

Figure 4.15 captures the effect of different aggregate types on the cracking resistance of asphalt mixtures at various conditioning levels. PG 67-22 asphalt mixtures (Figure 4.15.a) showed a similar trend as observed with the LWT test; Limestone with anti-strip > Crushed Gravel > Limestone without anti-strip > Semi-crushed gravel for Freeze-thaw conditioning. Further, for PG

70-22 asphalt mixtures, the SCB showed a trend of Crushed Gravel > Semi-crushed gravel > Limestone at control and FT-1. Whereas with FT-3, MiST 3500, and MiST 7000 level, Crushed gravel represented a higher value of J_d than Limestone and attributes the dominance of finer graded aggregates over high absorption aggregates. Further, Limestone performed better than Semi-Crushed Gravel at higher levels of conditioning and this is attributed to the combined effect of high aggregate angularity and low absorption. Similar to LWT, the SCB test was able to capture the effect of different aggregate properties.

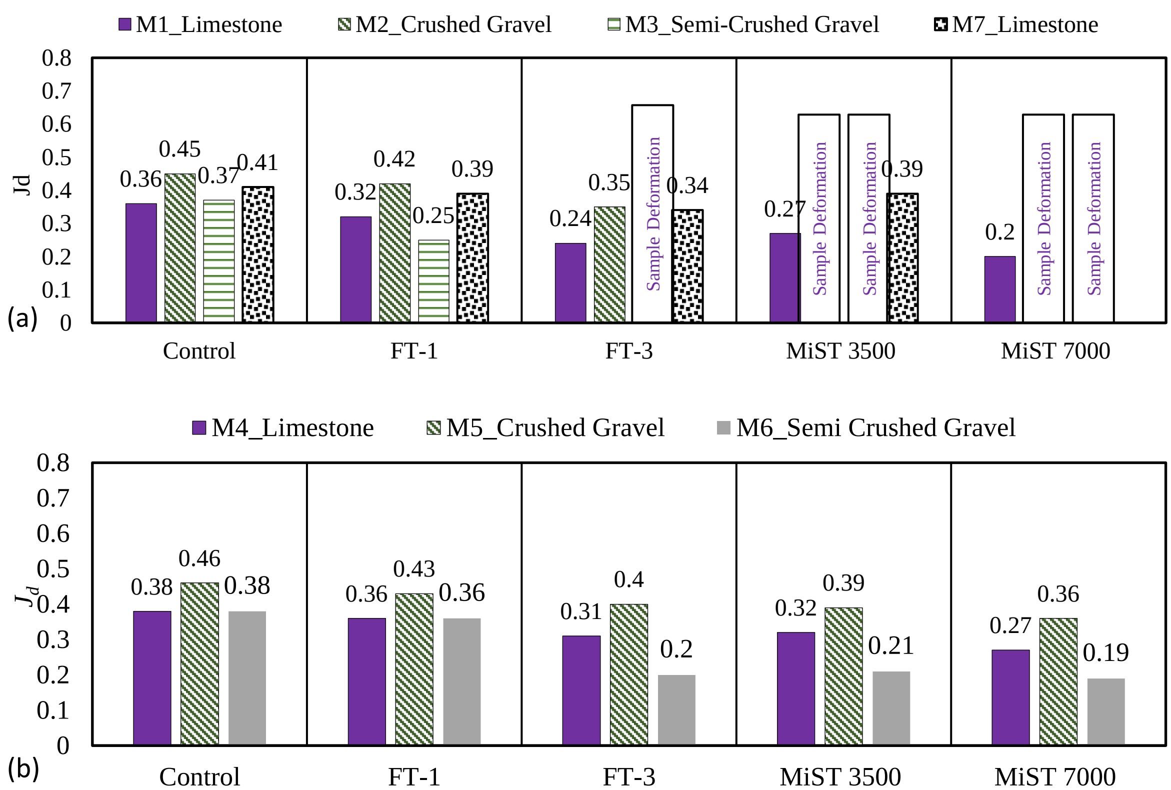

Figure 4.15. Effect of Aggregate Type on SCB-Jd value of; (a) PG 67-22 and (b) PG 70-22 asphalt mixtures

CHAPTER 5. SUMMARY AND CONCLUSION

The objective of the study was to evaluate the effectiveness of different mechanical laboratory test methods to ascertain the moisture sensitivity of asphalt mixtures. The study included an asphalt binder and an asphalt mixture experiment. The asphalt binder experiment used an unmodified (PG 67-22) and an SBS polymer-modified asphalt binder. The asphalt binders were subjected to five conditioning levels: a) RTFO, b) FT-1, c) FT-3, d) MiST 3500, and e) MiST 7000 levels. Subsequent rheological characterization of the conditioned asphalt binders was included in the asphalt binder experiment. The frequency sweep test and MSCR test was utilized for the rheological characterization of the asphalt binders.

The asphalt mixture experiment utilized a total of seven 12.5mm NMAS level 2 asphalt mixtures. Five conditioning levels similar to the asphalt binder experiment were included: a) control; b) FT-1; c) FT-3; d) MiST 3500; and e) MiST 7000. Further, a suite of mechanical tests, the LWT, the modified Lottman, and the SCB test were conducted to evaluate moisture sensitivity of the asphalt mixtures.

Table 5.1 present the summary for the evaluated asphalt mixtures at different conditioning levels. The capability of a mechanical test method for capturing moisture susceptibility of asphalt mixtures is evaluated and compared based upon the Pass/Failure criteria associated with the test method. As per Louisiana standard specifications for road and bridges (2016) [25], a maximum of 6mm rut depth @ 20,000 passes for 12.5NMAS, Level-2 wearing course was selected for LWT evaluation of moisture susceptible asphalt mixtures. Further, a minimum of 80% TSR is recommended for the modified Lottman test [44] . In this study, the use of SCB is recommended for moisture susceptible evaluation with a J_d-ratio of a minimum of 90%.

Figure 5.1 presents the number of times which the SCB and the modified Lottman test results comply with the LWT test. It is noted that the modified Lottman test shows similar characterized as provided by the LWT testing in seventeen cases. Further, the SCB test provided similar characterization as the LWT test in twenty-five cases.

Table 5.1. Asphalt mixture evaluation summary

Mixture Id:	Test (Failailure Criteria)	Control	FailT-1	FailT-3	MiST 3500	MiST 7000
M1	LWT (Rut > 6mm @ 20,000 passes)	Fail	Fail	Fail	Fail	Fail
	ModiFailied Lottman (TSR < 80%)	NA	Pass	Pass	Fail	Pass
	SCB (J_d-ratio < 90%)	NA	Fail	Fail	Fail	Fail
M2	LWT (Rut > 6mm @ 20,000 passes)	Pass	Fail	Fail	Fail	Fail
	ModiFailied Lottman (TSR < 80%)	NA	Pass	Pass	Fail	Fail
	SCB (J_d-ratio < 90%)	NA	Fail	Fail	Fail	Fail
M3	LWT (Rut > 6mm @ 20,000 passes)	Fail	Fail	Fail	Fail	Fail
	ModiFailied Lottman (TSR < 80%)	NA	Pass	Fail	Fail	Fail
	SCB (J_d-ratio < 90%)	NA	Fail	Fail	Fail	Fail
M4	LWT (Rut > 6mm @ 20,000 passes)	Pass	Pass	Fail	Fail	Fail
	ModiFailied Lottman (TSR < 80%)	NA	Pass	Pass	Pass	Pass
	SCB (J_d-ratio < 90%)	NA	Pass	Fail	Fail	Fail
M5	LWT (Rut > 6mm @ 20,000 passes)	Pass	Pass	Fail	Pass	Pass
	ModiFailied Lottman (TSR < 80%)	NA	Pass	Pass	Pass	Pass
	SCB (J_d-ratio < 90%)	NA	Pass	Fail	Pass	Fail
M6	LWT (Rut > 6mm @ 20,000 passes)	Pass	Pass	Fail	Pass	Fail
	ModiFailied Lottman (TSR < 80%)	NA	Pass	Fail	Pass	Pass
	SCB (J_d-ratio < 90%)	NA	Pass	Fail	Fail	Fail
M7	LWT (Rut > 6mm @ 20,000 passes)	Pass	Pass	Fail	Pass	Fail
	ModiFailied Lottman (TSR < 80%)	NA	Pass	Pass	Pass	Fail
	SCB (J_d-ratio < 90%)	NA	Pass	Fail	Fail	Fail

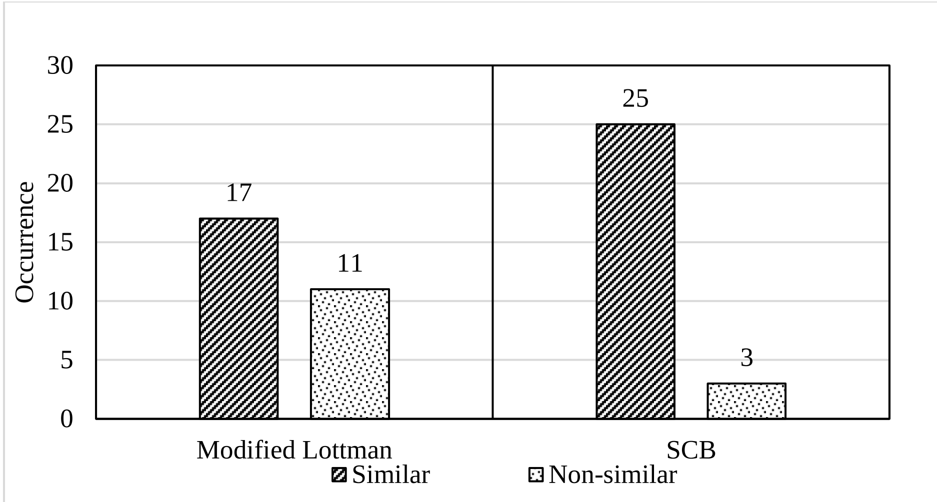

Figure 5.1. Complying test frequency

The following conclusions were drawn based on the findings of this study:

▪An increase in asphalt binder stiffness with the progressive increase in freeze-thaw and MiST conditioning was observed with frequency sweep test results (figure 4.1). Further, moisture conditioned PG 67-22 asphalt binder exhibited higher increase in stiffness from RTFO level than PG 70-22 asphalt binder.

▪Rutting parameter $(G^*/\text{Sin}\delta)_{50°C \,\&\, 5rad/s}$ of PG 67-22 asphalt binder was found to increase with Freeze-thaw and MiST conditioning when compared to RTFO. Whereas the SBS-modified PG 70-22 asphalt binder exhibited a minimal change in rutting parameter with moisture conditioning.

▪Freeze-thaw and MiST conditioning had a minimal effect on *Jnr* and *R* when compared to RTFO of the asphalt binder. Further, two clusters for each binder type were identified in the MSCR elastic response curve (PG 70-22 in the passing zone and PG 67-22 in the failed zone) suggesting no effect of freeze-thaw or MiST conditioning on the capability of the asphalt binder to meet the delated elastic response

▪A significant increase in rut depth @ 20,000 passes was observed with progressive increase in freeze-thaw and MiST conditioning. Further, moisture susceptibility of asphalt mixtures (M1 and M2) was captured at FT-1 or MiST 3500 moisture conditioned level

▪ The modified Lottman test did not show consistent test results with progressive moisture damage. In addition, the modified Lottman exhibited incompetence in capturing extensive moisture damage associated with moisture conditioning levels.

▪The SCB test showed potential to capture the effect of moisture damage on asphalt mixture specimens, a reduction in asphalt mixture stiffness was captured as a combined effect of change in tensile load and ductility of the asphalt mixture specimen.

▪ A new fracture energy parameter J_d was proposed for evaluating moisture susceptibility of asphalt mixtures. J_d was able to capture the progressive effect of moisture damage with incremental moisture conditioning.

▪The parameter J_d-ratio with a failure criterion of a minimum 90% showed a good correlation with LWT to identify moisture susceptible asphalt mixtures.

▪The LWT and the SCB tests were able to compare the effect of different aggregate properties, absorption, angularity, and gradation.

▪Among PG 67-22 asphalt mixtures, asphalt mixtures with low absorption aggregates showed better moisture resistance than high absorption aggregate mixtures. Furthermore, among high absorption mixtures, aggregate mixtures with higher coarse angularity exhibited better moisture resistance than lower coarse angularity mixture.

▪For SBS modified asphalt mixtures, high aggregate angularity with finer graded mixture exhibited higher moisture resistance than low absorption content aggregates mixture with coarse graded with mixtures

▪Asphalt binder test results exhibited weak relation with asphalt mixtures results. A minimal effect of rutting parameter ($G^*/\sin\delta$), elastic recovery (R), and Jnr was observed with freeze-thaw and MiST conditioning. However, an increase in moisture susceptibility of asphalt mixtures was observed among the asphalt mixtures evaluated.

5.1. Future Work

The SCB test was found to have a good correlation with the LWT test in predicting moisture damage in asphalt mixtures. To further investigate the potential of the SCB test following future recommendations are listed:

▪A wide range of asphalt mixtures properties must be evaluated with various moisture conditioning levels to validate the moisture on mixture sensitivity of the SCB test. The parameters must include but not be limited to:

a.modified asphalt binders (Like WMA, crumb rubber, polymer, bio-oils, plastic, etc.)

b.different aggregate properties (like shape, texture, and absorption),

c.different mixture gradation (like open-graded)

▪The ability of SCB test to predict moisture susceptible asphalt mixtures should be investigated by comparing the observed field performance to laboratory performance of moisture conditioning asphalt mixtures.

▪Standardization of the SCB as a moisture damage test should be done by including various field cores from different states.

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